R&D Plan Update for the Supernova / Acceleration Probe

The SNAP Collaboration

1 November 2003

Table of contents

List of Figures

List of Tables

Section 1. SNAP Mission Requirements and R&D Goals

1.1 Introduction

Our picture of the origin and nature of the universe has been transformed in the past few years by the first precision measurements of the fundamental cosmological parameters. Contrary to the expectations of the theoretical community that the mass density would equal the critical density, balancing the universe between eternal expansion and ultimate contraction, measurements reported in 1998 by two different groups studying supernovae concluded that the universe is expanding at an ever increasing rate and established a non-zero value for the cosmological constant. These results have since been confirmed by deeper and more precise studies of supernovae, and they are also consistent with independent data from cosmic microwave background measurements and from galaxy surveys. For example, the 2003 results from the Wilkinson Microwave Anistropy Probe Satellite reveal a universe that is flat, in agreement with inflationary models, but finds only ~27% of the total energy density is in the form of matter (and only 4% is baryonic matter), while the majority of the energy density is unknown – the so-called "dark energy."

These results have caused a great deal of speculation in the theoretical community and sparked a number of new theories regarding the dark energy that is driving the accelerating expansion of the universe. Understanding the nature of the dark energy is one of the key science goals identified by the Turner panel of the NAS and by the High Energy Physics Advisory Panel Subcommittee for Long-Range Planning.

In order to carry out more precise measurements of the cosmological parameters and determine the equation of state of the dark energy, we have proposed a dedicated satellite-based experiment, the Supernova/Acceleration Probe (SNAP). SNAP is a ~2-meter satellite telescope that will obtain a high statistics (~2000) calibrated data set of Type Ia supernovae with redshifts $z \leq 1.7$ and excellent control over systematic errors. To obtain high signal-to-noise, calibrated light curves and spectra for each supernova, SNAP is instrumented with a 0.7-square degree pixel-based imager with sensitivity to wavelengths ranging from 350–1700 nm, a near-UV to near–IR spectrograph and precision star guider CCDs. These instruments are integrated on a common focal plane. From these data we expect to measure the mass density of the universe to 2%, the density of dark energy driving the acceleration of the universe to 5%, and its equation of state to 5%. Time variation in the equation of state, a key attribute distinguishing other vacuum energies from a cosmological constant, could be detected. Detailed systematic studies will be carried out to account for potential biases or sources of error due to interstellar dust, galactic environment, etc.

In addition to the primary scientific goals of measuring the cosmological parameters, a rich program of auxiliary science can be carried out with SNAP's comprehensive wide-field data set. This includes study of weak and strong gravitational lensing that probe the dark matter content and distribution, time variable objects such as active galactic nuclei, gamma ray burst afterglows, outer solar system bodies, and the detailed population and distribution of galaxy types and stellar evolution.

In this document we summarize the work that has been accomplished to date and describe the remaining R&D necessary to prepare a Conceptual Design Report and obtain CDR approval for initiation of the engineering and design phase. In Section 2, the R&D plan for the SNAP instrumentation suite is described, including the visible and near-infrared sensors, filters, spectrograph, data acquisition, electronics and mechanical systems. Section 3 discusses the development of the SNAP calibration plan. Sections 4-6 are devoted to computing, telescope and spacecraft R&D plans. Sections 7 and 8 describe the system engineering and project management for the R&D phase. Schedules, manpower estimates and cost estimates are collected in a separate document.

1.2 High-Level Mission Requirements

The high-level mission requirements can be divided into two categories: requirements derived from the scientific goals of the project, and requirements derived from the need to withstand the rigors of launch and operation in space. These requirements and their derivation from the SNAP science goals are described in greater detail in the SNAP Mission Definition and Requirements Document and ongoing studies are further discussed in Section 2. Here we provide an overview of the most important requirements.

1.2.1 Science-driven instrument requirements

The SNAP satellite telescope and instrumentation suite is designed to provide observational data on a high statistics sample of supernova consisting of the following elements:

- Early detection of supernova.
- B-band rest-frame photometry to follow the supernova light curve.
- Supernova color at peak and near-peak brightness.
- Optical and IR spectra at peak brightness to classify the supernova.
- Photometric redshifts of the host galaxies prior to supernova follow-up.
- Medium resolution spectra/photometry for a limited subset of supernovae over the full light-curve.

Each of these observational requirements translates into a set of explicit requirements on the telescopes and instruments, also detailed in the SNAP Mission Definition and Requirements Document.

1.2.2 Requirements for operation in space

Launch and operation in space also impose requirements on the SNAP instrumentation suite and telescope. Many of these requirements involve design trade-offs and are still under development.

- The maximum launch payload limits both size and weight. At this time we are contemplating launch aboard a Delta IV-M, which can lift a maximum of 2800 kg to HEO. The Delta IV-M offers a 4-meter diameter payload fairing, which in principle could accommodate up to a 2.4-meter telescope.
- Available power on the spacecraft will be limited to what can be provided by on-board solar panels, estimated at approximately 300-400 W average power load.
- Thermal management is an important issue affecting all components. In the SNAP working concept, the instrument CCDs for optical and IR imaging will operate at 140 K for best performance, while the telescope will be maintained at room temperature in order to simplify pre-flight testing. This approach to thermal management is one of the recommendations of a trade study conducted at NASA-Goddard.
- Reliability is a major concern; all instruments must be space-qualified, demonstrate a minimum mean time to failure, and incorporate redundancy where possible. We are designing for a minimum of 4 years of operation.

1.3 R&D Goals

The R&D phase has five main goals:

1. Develop detailed requirements documents that will drive the later design and engineering phase of the project.
2. Develop and optimize concepts for all components to sufficient detail to insure a credible cost and schedule at CDR.
3. Identify the areas of highest risk and initiate design efforts and prototyping to mitigate cost and schedule risk during the construction phase.
4. Identify long-lead procurement items that could pace the final completion of the project, and initiate early discussions with potential vendors to minimize schedule and cost risk.
5. Identify and resolve instrumentation issues that affect the spacecraft and telescope design so that development can proceed in parallel.

The vast majority of R&D issues addressed in this proposal are paper studies that will document requirements, develop implementation concepts to meet the requirements, and simulate or otherwise validate these concepts. We will research existing or planned solutions that meet our requirements where these can be identified, and develop common solutions for all of the SNAP instruments wherever feasible. Scientific trade-off studies between competing designs or options will be carried out to determine the optimum design to meet SNAP's mission requirements.

Preliminary design work and prototyping will be initiated only where high risk and/or long lead items are identified with associated cost and schedule risks to the project. For example, the CCDs and associated readout electronics represent a new, attractive but unproven technology that will benefit from early design and prototype effort. The telescope, on the other hand, requires no real R&D because its optical parameters fall within the range of previously completed projects; nevertheless, a long lead time and high cost are associated with its procurement.

Section 2. Instrument R&D

This section describes the R&D plan for the SNAP instrument suite. We start with the conceptual design of the instrument. While this working concept will be subject to further scrutiny and optimization, it provides a solid foundation for a feasible and self-consistent observation strategy that realizes the primary scientific goals of SNAP. It also forms the basis for a program of limited and focused R&D that will lead to reliable cost and schedule estimates and a Conceptual Design Review (CDR) in two years.

The following subsections describe the detailed R&D plans for the components that make up the SNAP instrument suite: imager, spectrograph, and electronics and data acquisition. Each section includes a review of progress in the past year, a discussion of the main R&D issues and goals, and a summary of CDR planning activities, long-lead procurements, and risk assessment. Schedules, milestones, manpower, and costs are available in other documents.

Design and prototyping work for the SNAP instrument suite during the R&D phase is limited to the following areas:

- Characterization of commercially available IR detectors with 1.7 μm cutoff.
- Completion of development and commercialization of a new type of optical CCD featuring extended red response and enhanced radiation tolerance.
- Design of an integral field unit for the spectrographs.
- Development of custom integrated circuits for sensor readout.
- A few mechanical systems.

2.1 Instrument Conceptual Design

Eighteen months ago we concluded a scientific and technical trade study to determine the optimal configuration of the SNAP instrument suite. The conclusion was that a wide-field integrated optical to NIR imager with fixed filters provides the most efficient approach to collecting a high statistics, comprehensive and precisely calibrated data set of SNe, while meeting our criteria for technical feasibility, cost and schedule. A spectrograph is mounted on the backside of the focal plane and accesses light though a port in the focal plane. The observational strategy involves visiting the SNAP observation field every four days and stepping the focal plane across the field to collect a series of fixed duration exposures. Ground-based analysis of the transmitted data identifies Type Ia SNe and determines galaxy redshifts; with this information, SNe are selected for targeted spectrographic measurements at maximum brightness.

The present working concept of the SNAP instrument package is shown in Figure 1, Figure 2, Figure 3 and Figure 4 and consists of the following elements:

- *Imager.* The imager contains optical and IR sensors integrated on a common focal plane operated at 140 K, which is compatible with passive cooling. Fixed filters provide continuous overlapping photometry in nine bands over the visible and NIR wavelengths for B-band restframe measurements of SNe with redshifts up to z = 1.7. LBNL-developed CCDs cover 350 nm to 1000 nm. They are selected for their broad spectral response and high degree of radiation tolerance. A total of thirty-six, 3.5k $\times$ 3.5k, 10.5 μm CCD detectors are required. The NIR sensors are HgCdTe devices. Thirty-six 2k x 2k, 18 μm detectors will be used to cover the 900 nm to 1700 nm range.

- *Spectrograph.* Spectrographic information for each supernova at peak brightness is required. An instrument spanning the wavelength range of 350 nm to 1700 nm with a resolution $\lambda/\delta\lambda$ of ~100 can measure all the relevant features of Type Ia SNe over this range. A two-channel spectrograph utilizes the same focal plane as the imager. The sensors for the spectrograph consist of an LBNL CCD for optical wavelengths and a HgCdTe device for the near infrared.

- *Fine star guider.* Four small high speed CCDs are also mounted on the focal plane to provide feedback to the spacecraft during shutter-open time to help the attitude control system achieve the required pointing stability during the several hundred to several thousand second exposures.

- *Electronics systems*. Four systems of components make up the electronics suite. The first system includes clock and bias voltage generation, analog signal processing, and digitizing for the sensors. In the case of the CCDs, we have developed a custom integrated circuit (ASIC) for analog signal processing and digitization. In the case of the NIR, we continue to follow the development at Rockwell of an ASIC that fully manages the readout of their HgCdTe devices. The second system funnels the data streams from the sensors into the instrument mass memory system performing lossless compression on the fly. Third is the system that configures the electronics subsystems and monitors the instrument environment. Examples of this include setting operating voltages inside the front-end electronics and monitoring the sensor temperatures. The fourth system oversees the execution of the observation plan that performs such activities as opening and closing the shutter, cycling the calibration lamps, and transitioning the readout electronics from image capture to readout mode.

- *Mechanical systems*. The mechanical components of the instrument comprise a mechanical shutter, a combined function particle/thermal/stray-light shield, a 140 K cold plate to which the imager sensors and spectrograph are mounted, thermally isolating kinematic mounts by which the cold plate is attached to the telescope mechanical structure, flexible thermal links between the cold plate and the radiator, and the radiator itself that provides passive cooling of the cold plate and its sensors.

2.2 Instrument R&D Plan

The SNAP instrument R&D is organized in six working groups studying visible sensors, NIR sensors, spectrograph, fine star guider system, mechanical and thermal design, and electronics.

The goal of the R&D period is to develop a conceptual design with an associated cost and schedule that can serve as the basis for the Conceptual Design Review (CDR). In addition, we seek to identify and mitigate project risk due to unproven technologies and long-lead procurements. The main deliverables of the R&D period are a Conceptual Design Report including a formal set of requirements linked to the science goals, a preliminary interface control document that defines system components and their interactions, a detailed schedule, and a reliable cost estimate.

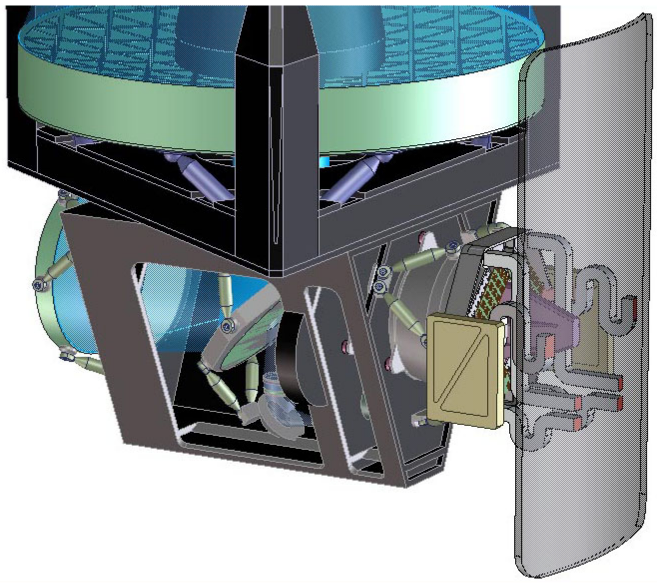

Figure 1. SNAP instrument installed in the optical bench.

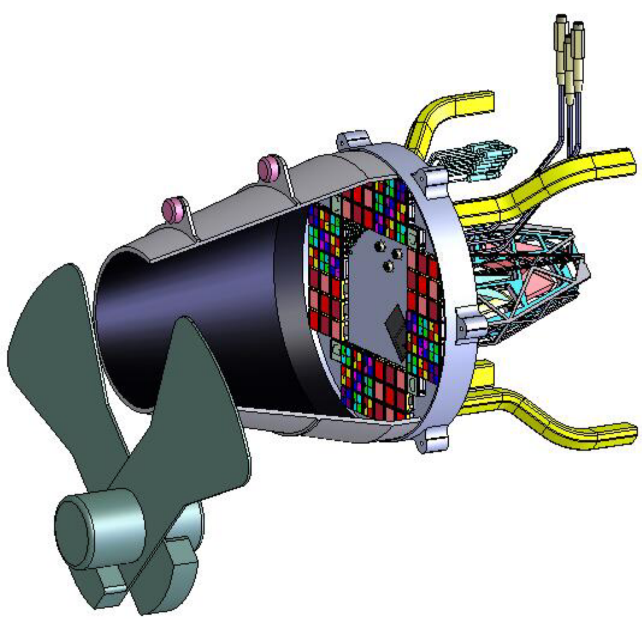

Figure 2. Cutaway view of the instrument package.

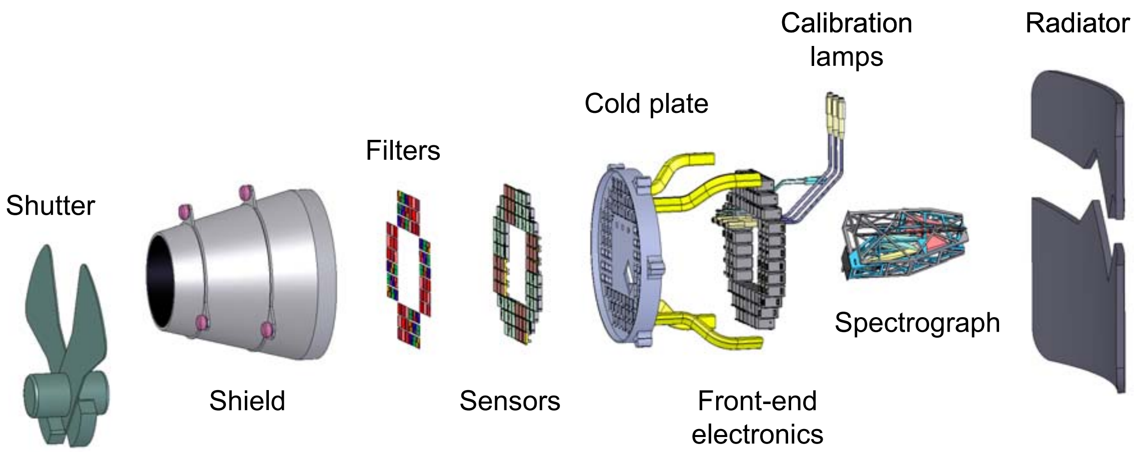

Figure 3. Exploded view of the SNAP instrument package.

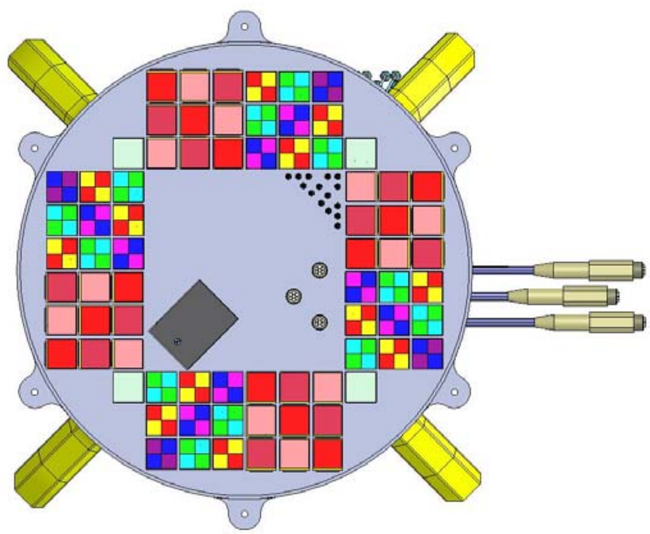

Figure 4. Front view of the SNAP focal plane.

2.3 Near Infrared (NIR) Imaging R&D

2.3.1 Introduction

For supernovae at redshift above z =1, the cosmological redshift moves the restframe visible emission at ~500 nm beyond the long-wavelength cutoff of the optical CCD detectors and into the near-infrared (NIR). Supernova photometry must be done at a common rest-frame (blue) wavelength if the supernovae are to be used as standard candles; hence, NIR imaging at wavelengths of 0.9–1.7 μm is a critical aspect of the mission. NIR photometry is also essential to the diagnosis and correction of systematic errors due to extinction including those SNe with z<1, as all known forms of dust grains give much less extinction in the NIR than in the visible. Furthermore, the NIR observations greatly expand the science reach with high statistics, high-z, wide-field measurements not accessible with any other operational or proposed instrument.

2.3.2 NIR system baseline

The NIR system will be an integral component of the focal plane. In the baseline concept, thirty-six 2k × 2k near-infrared imaging sensors covering a total of 0.34 square degrees will be placed in four 3 × 3 arrangements symmetric to the CCD placement. The NIR sensors will have a cell pitch of 18-20 μm, resulting in a total of about 150 Megapixels for the NIR system. The leading candidate for the NIR sensors are HgCdTe focal plane arrays (FPA). These devices exhibit low read noise and dark current while providing excellent quantum efficiency (typically 50%-80% over the wavelength interval 0.9 -1.7 μm). Two companies are producing large, astronomical devices: Rockwell Science Center (RSC) who offer a 2048 x 2048 pixel HgCdTe sensor hybridized onto the Hawaii 2-RG (H2RG) multiplexer, and Raytheon Vision Systems (RVS) who have developed a 2.5 μm 2048 x 2048 device for the VISTA project. RVS is currently developing a short wave (1.7 μm) version of their VISTA FPA for SNAP. Both RSC and RVS devices have been successfully used at ground-based telescopes and it is expected that both companies will be capable of producing a NIR device that will be suitable for the SNAP mission. A cutoff at a wavelength of 1.7 μm is a good match to SNAP since the sensors are blind to the thermal background radiation from the warm telescope. The HgCdTe technology is also the leading candidate for the NIR sensors on the spectrograph. Table 1 lists the performance specifications for the SNAP NIR system. An important element of the R&D phase is the development of the NIR science requirements. The current performance specifications represent our best current estimates. In a separate development, Sensors Unlimited (SU) is developing an InGaAs diode array for SNAP that will be hybridized to an H2RG multiplexer by RSC. InGaAs has a natural cutoff near 1.7 μm and shows promise as an alternative technology to HgCdTe.

Table 1. SNAP NIR Performance Specifications

Parameter	Specification	Reasoning
Field of View	~ 0.3 square degrees	Match CCD FoV to observe every SN in every color
Plate Scale	0.17 arcsec / pixel	Achieve photometric accuracy with at most 2 x 2 dithering
Wavelength Coverage	0.9 μm - 1.7 μm	- overlap with CCD - reach into deceleration phase - observe restframe B-band out to z = 1.7
Read Noise	< 5 e^- (w/ multiple reads)	Assures that photometry is zodiacal light limited
Dark Current	< 0.02 e/pixel/sec	
Quantum Efficiency (Detector)	> 60%	To achieve adequate S/N to study SNe at z = 1.7 within time constraints
Filters	Three special filters	To obtain redshifted 'B'-band steps from 0.9 to 1. 7 μm

2.3.3 HgCdTe FPAs

HgCdTe is a ternary semiconductor compound, which exhibits a wavelength cut-off proportional to the alloy composition. This allows the cut-off wavelength and thus the operating temperature, to be "tailored" to the specific application. The SNAP focal plane can be passively cooled to an operating temperature of 140 K. At this temperature HgCdTe is expected to have a dark current below the SNAP specification. Experience with 1.7 μm large-format HgCdTe detectors is limited to the Wide Field Camera 3 (WFC3) project on the HST. RSC has produced a large number of devices for WFC3 (> 60) resulting in only two suitable for flight. These two devices fall short of meeting SNAP performance specifications, particularly in the area of readout noise, and a development program is required to correct this (see 2.3.3.2). Nevertheless, the SNAP project will be able to benefit from the extensive WFC3 experience, inheriting much of the technology development. While InGaAs shows promise as a short-wave detector, experience with large-format InGaAs detectors is virtually non-existent. Until we acquire such experience, InGaAs will remain as an alternative technology for SNAP.

In the current design, the SNAP focal plane will utilize HgCdTe infrared detectors that have been specifically developed to meet SNAP science requirements. The actual detector is composed of a thin layer (10 to 20 μm) of HgCdTe with metallized contact pads defining the active area. Photons with energy greater than the semiconductor band-gap energy excite electrons into the conduction band, thereby increasing the conductivity of the material. The FPA is a hybrid consisting of a highly integrated CMOS multiplexer and an array of infrared sensitive (HgCdTe) detectors. The two pieces are indium bump-bonded together. The multiplexer is an array of discrete read-out transistors and, unlike a conventional CCD, can be read non-destructively.

Rockwell Science Center (RSC) has produced large format HgCdTe infrared focal plane arrays and has a long history of developing devices for the astronomical community (NICMOS 256 x 256 FPAs, WFC3/HST 1k x 1k, University of Hawaii, ESO, Subaru 2k x 2k). Until recently, the standard process employed by RSC to fabricate arrays has been liquid phase epitaxy (LPE). In the last several years, RSC has developed a process of fabricating detector layers in HgCdTe using molecular beam epitaxy (MBE).

For SNAP, RSC would utilize MBE technology for the NIR diode array, mated to the H2RG multiplexer. RSC feels that MBE offers them the best process control needed to tailor the device properties to SNAP specifications. In particular they believe that MBE will achieve improved quantum efficiency at short wavelength and will eliminate image persistence through lattice matching of the HgCdTe to the CdZnTe substrate, and reduce the intra-pixel variation observed in LPE technology devices. The H2RG incorporates multiple output modes, operational modes and data rates.

Building on their long-standing experience with developing large-format astronomy arrays in InSb (Aladdin, Orion devices) and lately also in HgCdTe (VIRGO) technology, Raytheon (RVS) is now competing for SNAP NIR detector development. RVS is taking a different approach for the detector material growth process. They feel that LPE offers them the best control of the HgCdTe material properties and will result in the best match to SNAP specifications. Both RSC and RVS have extensive experience with both LPE and MBE and have chosen their individual approach based on that experience. RVS will build on their experience with their VIRGO 2K x 2K multiplexer that has now been incorporated in devices produced for the VISTA project.

Table 2. The specifications for the SNAP NIR focal plane array detectors

Parameter	**Specification**
Detector technology	MBE or LPE HgCdTe
Active area format	2048 x 2048 pixels
Buttability	4-side
Pixel pitch	18-20 μm square
Fill factor	$\geq$ 0.90
Outputs	16 or 32
Power dissipation	$\leq$ 100 mW

Measurements that are important to SNAP are read noise, dark current, quantum efficiency (QE) and intra-pixel variations. Below we list the status of these measurements. We also will measure other detector characteristics such as persistence, inter-pixel variations and the temperature dependence of relevant parameters.

2.3.3.1 Dark current

Currently, the performance specification for the NIR detector dark current is <0.02 e/pixel/s. For a nominal 300-second exposure this corresponds to 6 e. For high quantum efficiencies (> 60%) and a read noise of 5 e, this corresponds to a S/N of 3 for a z=1.7 type Ia SN, two magnitudes below peak intensity. This noise level is about half the zodiacal background light in favorable regions in the north and south ecliptic poles. These practical considerations make it difficult for SNAP to reliably detect SN beyond z=1.7. While further studies are needed to establish the precise dark current requirement for SNAP, the current specifications strike a balance between integrated dark current and read noise as the dominant source of noise.

The dark current depends sensitively on the cutoff wavelength of the HgCdTe detector and the temperature. The Detector Characterization Lab (DCL) at the Goddard Space Flight Center (GSFC) has measured the dark current at 150 K for a sequence of 1.7 μm devices produced by RSC for WFC3. As RSC has gained more experience, the dark current has been dropping and a number of devices have dark currents below the WFC3 performance specification of 0.1 e/pixel/s. A rule of thumb (not yet confirmed for these devices) is that the dark current should drop by a factor 7-10 for every decrease of 10 K in temperature. We are thus confident that the SNAP dark current specification of 0.02 e-/pixel/s at 140 K is achievable by RSC and we expect that devices produced by RVS will have comparable dark current performance.

2.3.3.2 Read noise

The SNAP specification of 5 e- assumes that the intrinsic read noise for a single CDS read will be 10 e- and that 4 reads at the beginning and end of an exposure will reduce this by a factor of $\sqrt{4}$. This noise performance has been achieved for all Hawaii multiplexers mated to HgCdTe material with a cut-off of 2.5 μm or greater. In principle, read noise should be independent of the wavelength cut-off, but for WFC3 devices this turns out not to be the case.

The Detector DCL at the NASA GSFC has performed extensive measurements on 1.7 μm devices during the selection of NIR detectors for the WFC3. The selected flight unit shows a quantum efficiency of 81% at 1.5 μm and greater than 40% at a wavelength of 1.1 μm, read noise of 24 e- (for a single CDS read), and a mean dark current of 0.04 e-/pixel/s (at 150K). While this read noise level is acceptable for WFC3, it is more than a factor of two larger than the current specifications for the SNAP NIR sensors. RSC has used a modified process during the final lot production for the WFC3 devices to reduce the read noise. Through a change in the order of the processing steps, the read noise was cut in half (to 10-12 e- for a single CDS) but the quantum efficiency for these devices was low. RSC believes they understand the mechanisms behind this behavior and that they will be able to control for this in future lots. For the production of high performance SNAP devices, RSC is budgeting two process lots in a parallel approach. One approach is to utilize a low risk evolutionary process to improve read noise and QE while the second approach will be devoted to improving the quantum efficiency for the low read noise process production as used for the WFC3 final lot.

RSC is confident that within the R&D period, they will be able to produce devices that meet the SNAP read noise performance specifications. Nevertheless this remains an important challenge for the NIR R&D program.

At present Raytheon has limited manufacturing experience with short wavelength devices and no dark current or noise measurements of 1.7 μm detectors are available. However, they have produced devices with a 2.5 μm cutoff for the VISTA project and they are confident that with their multiplexer technology and the LPE process, they will be able to meet SNAP specifications.

2.3.3.3 Quantum efficiency

The SNAP near-infrared quantum efficiency specifications of > 60% results from the need to detect Type Ia SNe out to redshifts of z = 1.7 within time constraints of the SNAP observing program. For WFC3 the QE has steadily improved as RSC gained more experience with the MBE growth process and the best devices show a QE that increases roughly linearly with wavelength from about 40% at 1.1 μm to more than 80 % at 1.6 μm.

Raytheon has claimed they understand the problem with this droop in QE at low wavelengths and that their LPE growth process combined with their VISTA multiplexer will not show this behavior.

RSC believes that they understand the MBE parameters that control QE and have produced devices that seem to validate this claim. The QE for these new devices is uniformly high and exceeds the SNAP NIR specifications. At the same time these devices show a large read noise. RSC is approaching these issues and they believe they can control the production process and produce devices with high QE and low read noise. We are thus hopeful that the SNAP QE solution will be inherited from the WFC3 development.

2.3.3.4 Intra-pixel variations

Accurate photometry (~2% overall statistical, ~2% relative systematic) is the current NIR performance target until SNAP science driven requirements have been passed down to the detector level. Sensitivity variations on the scale of a single pixel can significantly reduce photometric accuracy of under-sampled images. In the near infrared, diffraction dominates the point-spread function at all wavelengths. At 1 μm the Airy disk is Nyquist under-sampled by about a factor of three for a pixel size of 18-20 μm. Intra-pixel variations for PACE detectors have been measured by Gert Finger (ESO) and found to be quite large.

SNAP simulations have indicated that any reasonable intra-pixel variations can be corrected with 2x2 dithering, yet this remains to be verified by measurements. To this end, the Michigan group has built a spot projection system (‘spot-o-matic’), which will allow us to project spots of order ~ 2 μm and above onto various devices. By degrading the focus we will be able to project diffraction limited images onto prototype detectors.

By dithering these images we can verify that correction of inter-pixel variations and diffraction limited reconstruction of images can be achieved.

RSC believes intra-pixel variation will be reduced through the MBE process as material deposition - and thus the fields within the HgCdTe material - can be better controlled, resulting in improved collection of charge. In contrast, Raytheon focuses on improving intra-pixel variations through the multiplexer design and they believe that their development will result in more uniform charge collection right to the edges of the pixels through larger charge collection area. Our tests will address this issue.

2.3.4 InGaAs detectors

At JPL material studies on InGaAs detectors from Sensors Unlimited (SU) and from Microdevices Laboratories (MDL) were performed. Two types of InGaAs materials from SU (128 element line arrays with 1.7 μm and 2.2 μm cutoff) and a 1.7 μm cutoff photodiode from MDL were tested. A downward shift in the wavelength cutoff was observed at low temperatures for all devices. This is a characteristic of the arsenites. Sensors Unlimited will hybridize InGaAs detector material to RSC multiplexers to facilitate evaluation of the material. In general, the InGaAs array technology is less mature than HgCdTe and it has to be seen if InGaAs can become a viable detector option for SNAP. The NIR group will perform all tests necessary to achieve realistic assessment of the arrays.

2.3.5 Progress in the past year

Over the last year the SNAP NIR program has crystallized with several important developments. 1) There are now two competing vendors for HgCdTe FPAs (Rockwell Science Center (RSC) and Raytheon Vision Systems (RVS). 2) An alternative sensor technology (InGaAs) is under investigation. 3) A strong NIR team has been assembled to characterize devices (Caltech, IU, JPL, UCLA, UM). 4) A detector procurement and development program has been put in place. 5) An active program of device characterization is under way. 6) Laboratory facilities are in place at Caltech, JPL, and the University of Michigan.

In order to gain experience with NIR detector technology and to prepare for the testing and evaluation of HgCdTe detectors, the Michigan group has set up an infrared detector laboratory. Two read-out controller systems from Astronomical Research Cameras (ARC) were purchased and interfaced with a test dewar. During the past 12 months multiplexers from RSC (H1RG) and from RVS (VISTA 1k, VISTA 2k) were obtained and interfaced to the system. Noise and dark current measurements on these devices demonstrated the ability to test HgCdTe FPAs with the required sensitivity. Within the SNAP NIR group, Michigan has the unique capability to project micron size spots at NIR wavelength onto FPAs inside a test dewar. This capability is essential to measure intra-pixel variations.

The IU group has developed a QE measurement system, which has been set up at the Michigan lab. Using a calibrated lamp and a calibrated photodiode this system can illuminate detectors with an irradiance calibrated to an absolute accuracy of 5% and a uniformity of 0.5% across a full FPA. This source will also be used for inter-pixel and conversion gain measurements.

The Caltech group has recently set up a laboratory to test SNAP devices and acquired a 16-channel ARC control and readout system, which will be used with an existing dewar. The group will focus on noise, dark current and QE measurements with the goal of complete electronic characterization of the devices to be tested. They also are investigating designs for automating the large scale testing of SNAP devices. The UCLA group, under subcontract with Caltech, will concentrate on the characterization of devices supplied by RVS whereas Caltech will characterize the RSC sensors. All devices will be exchanged between the SNAP NIR laboratories for concurrence testing.

The JPL group has begun to evaluate InGaAs detectors as an alternate sensor technology for SNAP. They will share the 16-channel ARC array controller used by the Caltech group. They will be responsible for characterizing the InGaAs FPA developed by Sensors Unlimited /RSC.

2.3.6 NIR R&D plan

The primary R&D goal is to refine our requirements for the wide-field NIR imager based on additional mission simulations and evaluation of NIR detector devices, and to produce a realistic cost and schedule estimate for the CDR. This will conclude in the NIR systems requirements specification document at the end of the R&D phase. An important element of this task is to develop detailed acceptance criteria and qualification procedures for the NIR devices in coordination with the vendors. The mechanical and thermal design for the NIR and optical imagers are closely coupled in the integrated focal plane concept and will be developed jointly with LBNL.

2.3.6.1 Detector characterization and testing

The characterization and evaluation of NIR detectors are a high priority for the NIR group. The Infrared Detector facilities at the University of Michigan, Caltech and JPL provide the required environment for the comparative testing and evaluation of industry supplied infrared sensors and will produce test data relevant to the success of the SNAP science program. A contract for the development of SNAP specific NIR detectors has been put in place with RSC, RVS and SU. Table 3 shows the delivery schedule. Delivery has already begun for multiplexers that will be used to test our interfaces and facilities. Over the next 14 months a variety of devices will be developed, starting with engineering grade FPAs and ending with science grade FPAs optimized for SNAP requirements. The NIR group will measure detector properties (read noise, dark current, intra-pixel variation, persistence, quantum efficiency) as functions of environmental parameters (thermal conditions, operating modes, radiation exposure). The results of those measurements will allow us to specify detector characteristics, which, together with the science requirements established at the beginning of the R&D program, will define the acceptance criteria for the SNAP NIR flight devices. Our plan is to concentrate on the following main issues during the R&D:

- Characterize the read noise, dark current and QE of NIR FPAs
- Explore alternatives to HgCdTe detector technology
- Perform comparative testing of multiplexers and NIR devices from different vendors
- Study intra-pixel variations and establish impact on accurate photometry
- Determine optimum sampling strategy for reducing read noise
- Establish schemes for vetoing cosmic rays through multiple sampling
- Establish facilities for receiving and qualifying NIR FPAs
- Optimize calibration techniques and strategies
- Characterize spurious read noise due to trapped charges and establish optimal reset scheme
- Develop a mechanical and thermal concept for NIR imager in an integrated focal plane
- Bench test thermal and mechanical design
- Provide input for simulation group and compare simulation results against measurements
- Establish flight grade requirements for NIR detectors

We note that other projects also plan on extensive NIR imaging capability, for example the WFC3 on HST and the NGST, and we will consult extensively with their design groups to take advantage of their development efforts.

Table 3. Device Delivery Schedule

Device	Vender		Grade	size	Initial Site	Delivery Date
H1RG	RSC	mux	engin.	1k × 1k	UM	in hand
VIRGO-2k	RVS	mux	engin.	2k x 2k	UM	in hand
VIRGO-1k	RVS	mux	engin.	1k × 1k	UM	in hand
VIRGO-1k (2.5 μm cutoff)	RVS	FPA	near science	1k × 1k	UM	in hand
H2RG	RSC	mux	engin.	2k x 2k	UM	in hand
H2RG	RSC	FPA	engin.	2k x 2k	Caltech	March 2004
H2RG	RSC	FPA	engin.	2k x 2k	UM	April 2004
VIRGO-1k	RVS	FPA	engin.	1k × 1k	Caltech/UCLA	April 2004
InGaAs/H1RG	SU/RSC	FPA	engin	1k x 1k	JPL	April 2004
VIRGO-1k	RVS	FPA	engin.	1k × 1k	UM	May 2004
H2RG	RSC	FPA	engin.	2k x 2k	UM	July 2004
VIRGO-2k	RVS	FPA	science	2k x 2k	Caltech/UCLA	Aug. 2004
VIRGO-1k	RVS	FPA	engin.	1k × 1k	UM	Aug. 2004
VIRGO-2k	RVS	FPA	science	2k x 2k	UM	Sep. 2004
H2RG	RSC	FPA	science	2k x 2k	Caltech	Nov. 2004
H2RG	RSC	FPA	science	2k x 2k	UM	Dec. 2004

2.3.6.2 Filter design

There are several options for fixed filters that are being evaluated. The fixed filters may be mounted just above the sensors or deposited on the sensors as part of the sensor processing. The NIR group will provide input to the filter design and filter performance specifications.

2.3.6.3 Mechanical and thermal design specifications

The NIR array will be integrated along with the CCDs to produce the complete SNAP focal plane imaging system. This system will be passively maintained at a temperature of 140 K. As part of the R&D effort, we will work closely with the CCD and SNAP System Engineering to produce an overall focal plane mechanical and thermal design which ensures the proper performance of the NIR camera. Issues to be addressed include:

- Thermal coupling (both radiative and conductive) of the HgCdTe devices to the focal plane substrate and surrounding instrument to minimize temperature gradients across individual devices, as well as the total array, in order to minimize intra-pixel differences in quantum efficiency, dark current, and noise.
- Mechanical mounting which minimizes residual stress on the devices, maintains accurate spatial alignment of the devices within the array, adequately isolates the devices from launch vibration, and minimizes thermal stress on the devices during initial cool-down on orbit.

2.3.7 CDR planning

The deliverable at the end of the R&D phase is a cost and schedule estimate for construction of the NIR imaging system. Assembly of a NIR detector test system will be essential in establishing that requirements are met and in firming up cost estimates. It is likely that much of the work for the NIR optical and mechanical systems will be done in parallel with the primary optical and mechanical assemblies.

2.3.8 Risk assessment and risk mitigation

The production and availability of the desired 1.7 μm cut-off FPA device depends on the commercial vendors. Limited space experience with NIR devices (HgCdTe or InGaAs) exists. The SNAP NIR system will have the largest number of infrared detectors ever and thus presents unique challenges. HgCdTe focal plane arrays are a relatively new but rapidly developing technology. The R&D phase will be used to mitigate risks in key detector technology areas such as noise, intra-pixel variation and qualification testing. We intend to mitigate these risks by extensively testing the HgCdTe devices and by working closely with the JWST and WFC3 IR detector groups.

2.4 CCD R&D

2.4.1 Introduction

LBNL has developed a new type of large-format CCD based on n-type high-resistivity silicon with p-channels.[1] The back-illuminated CCDs are 200-300 μm thick and the substrate is fully depleted by the application of an independent voltage through the front side to an optically transparent backside contact. The extended red response and the increased radiation tolerance compared to conventional n-channel CCDs make these devices a suitable choice for the SNAP visible sensors.

LBNL CCDs have already been deployed at ground-based telescopes. The NOAO September 2001 newsletter cover featured an image of the Dumbbell Nebula NGC 6853 (see Figure 5) acquired with an LBNL 2k x 2k CCD taken at the WIYN 3.5 m telescope at Kitt Peak National Observatory (KPNO). All three false colors made use of the extended red response of the CCD. A supernova spectrum taken by the LBNL Supernova Cosmology Project on the RC Spectrograph at KPNO is shown in Figure 6. LBNL CCDs have also been installed at KPNO on the Multi-Aperture Red Spectrometer (MARS) and on the Lick 3 m Coude Eschelle Spectrograph.

The research effort on LBNL CCDs is focused on two primary activities: commercialization of the device fabrication process, and design enhancements to further enhance radiation tolerance and to improve spatial resolution. The CCD packaging and testing efforts function in support of this program, providing packaged devices that are used to obtain imaging performance measurements as well as radiation testing data.

As a back-up option to CCDs, we are also exploring the possibility of using silicon PIN diodes hybridized to a multiplexer such as those used to read out HgCdTe pixel detectors. Silicon PIN diodes have not been used in astronomical applications yet, and further development would be required for SNAP. The R&D program is focused on determining whether PIN diodes meet the SNAP scientific requirements when operated at cryogenic temperatures and subject to radiation.

2.4.2 LBNL CCD technology

Figure 7 compares a conventional back-illuminated CCD with the LBNL technology. LBNL CCDs are fabricated on float-zone refined high-resistivity (~10 kΩ-cm) n-type silicon. Holes, rather than electrons, are collected in the potential wells. An indium-tin oxide (ITO) coating on the back surface provides three functions:

[1] S. E. Holland, D. E. Groom, M. E. Levi, N. P. Palaio, S. Perlmutter, R. J. Stover, and M. Wei, "Large Format CCD Image Sensors Fabricated on High Resistivity Silicon," pp 179-182, Proc. 1999 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, June 10-12, Karuizawa, Nagano, Japan.

1. A contact for a bias voltage that completely depletes the substrate so that photo-generated charge from the whole volume is collected.
2. A transparent window, permitting back illumination.
3. Part of the back-surface anti-reflective (AR) coating.

Since the devices are thick, they exhibit excellent quantum efficiency in the red until just below the silicon bandgap at 1050 nm. Interference fringing, which is a problem in thin devices at wavelengths where the absorption length is greater than the device thickness, is completely absent.

Since blue light is strongly absorbed in the gate structure of any front-illuminated CCD, the CCDs used in astronomy are usually thinned and back-illuminated. For most devices (~20 μm thick 10–50 Ω–cm epitaxial layer), this means thinning to about 20 μm. The thinning results in transparency in the red, resulting in a loss of quantum efficiency (QE) and fringing due to multiple reflections. For the LBNL devices this aggressive thinning process is both unnecessary and undesirable.

Advantages of the thick, fully-depleted LBNL CCDs include:

1. High quantum efficiency (QE) up to wavelengths approaching the silicon bandgap at just above 1050 nm, where silicon becomes transparent.
2. Absence of fringing. The interference patterns that are present in thinned spectroscopic CCDs are completely absent in these thick devices.
3. Good blue response without special processing and without UV flooding. A normal CCD exhibits field inversion near the back surface, resulting in the loss of QE for blue light where the absorption length is very short. Since holes, rather than electrons, are collected in the CCDs, the problem does not exist and the fully-depleted substrate has no field-free region.
4. Radiation tolerance due to the very low concentrations of phosphorus and oxygen in the n-type high-resistivity silicon.
5. Large well-depth of 300,000 e^- for 15 μm pixels and 130,000 e^- for 10.5 μm pixels.
6. Low noise readout.
7. Control of lateral charge diffusion by over depletion of the substate.

We have tested a range of CCD architectures with pixel sizes of 10.5, 12, and 15 μm and pixel counts up to 4800 x 1800. In Table 4 we show routinely achieved results for a variety of CCD characterization parameters. A measurement of backside-illuminated quantum efficiency is shown in Figure 8. The broad spectral sensitivity is readily apparent.

The commercialization of this technology is well underway. CCDs have been successfully fabricated by DALSA Semiconductor on 100 mm and 150 mm wafers, but the process requires post-processing at LBNL. We are exploring several fabrication scenarios that are consistent with the quantities and timescale required by SNAP.

Table 4. LBNL CCD characteristics.

Parameter	Typical value
Dark current	0.001 e/s/pixel @ 140 K
Read noise	2 e @ 50 kHz; 3 e @ 100 kHz
Sensitivity	3.5 μV/e
Well depth	300 ke for 15 μm 130 ke for 10.5 μm
Charge transfer inefficiency	$2x10^{-6}$ @ 140K

2.4.3 CCD production status

We have fabricated CCDs in a variety of formats up to 2k x 4k on 300 μm thick, 100 mm wafers at the LBNL Micro Systems Lab (MSL), a facility intended primarily for research and development. In order to produce thick, fully-depleted CCDs in larger quantities with industrial quality control, we have been processing waferts at DALSA Semiconductor Corporation over the last several years using their standard CMOS process. DALSA processes 675 μm thick, 150 mm wafers, which must be thinned to 200–300 μm for use in scientific imaging. We have made unthinned, fully processed CCD wafers at DALSA and they have been of high quality, with excellent performance for front-illumination, demonstrating the process flow up to wafer thinning. Figure 9 shows a 150 mm wafer fabricated at DALSA containing a variety of CCDs and Figure 10 shows a front-illuminated image from a 2k x 4k device.

We have attempted to have DALSA fully process thinned wafers, but breakage on their fully automated equipment is an issue. We did receive one thinned (300 μm) large format CCD wafer from DALSA that has been operated successfully in backside illumination tests.

Figure 11 shows some back-illuminated images taken with one device from this wafer. We believe this to be the world's first commercially fabricated p-channel, fully-depleted, back-illuminated CCD.

In the last year, much LBNL effort has gone into developing a hybrid business model in which all of the front-side processing, except metallization, is completed at DALSA. This includes all the conventional CMOS process steps. LBNL has the wafers thinned and does the backside in-situ doped polysilicon (ISDP), which requires a high temperature furnace (600° C). (Alternately, this step can also be done at DALSA because minimal handling is required.) The front-side contact etch and Al metallization must take place after ISDP to avoid the high temperature, followed by application of the back-side indium-tin oxide (ITO) and SiO_2 anti-reflective (AR) coating. Experience has shown that the MSL is better suited for executing these process steps on thinned, 150 mm wafers.

LBNL has developed careful handling procedures and equipment modifications to protect the backside of the wafer during the final fabrication steps. Backside scratches through the ISDP layer are fatal for fully-depleted operation. To first order, our experience is that the main culprit is particles and that they can be removed with mechanical action (scrubbing). Procedures we have adopted include:

- Particle removal via wafer scrubbing is the most effective technique to date.
- Use of wear resistant materials on vacuum chucks and wafer handlers where possible (DuPont VESPEL® is effective but does shed particles).
- Avoid use of silicone parts. Particles deposited by these cannot be remove with scrubbing.
- First wafers through equipment (coater, aligner) tend to have significantly higher particle counts.
- Photoresist aerosol particles are too large to be removed with plasma ashing and require the addition of a solvent to the scrubbing soap solution.

LBNL has acquired a 150 mm aligner for the etch and metallization steps, and has also performed some trial runs with CCDs on 150 mm wafers from DALSA. Two issues have been identified that are currently the focus of our CCD production R&D effort.

- The grinding and polishing of 675 μm wafers to 200-300 μm must meet stringent requirements on flatness and surface quality. To date we have one qualified vendor who meets our flatness requirements. We are also looking into chemical polishing.
- The MSL etcher is an older model that lacks sufficient controls to avoid arcing and burning during the etching of large format CCDs. We are working with the Berkeley campus to use their etcher and considering the purchase of a better etching machine for the MSL.

Resolution of the thinning and etching issues will clear the way to a demonstration that CCDs meeting SNAP requirements can be produced in sufficient quantities, and will also allow us to make LBNL CCDs more widely available for ground-based astronomy.

2.4.4 CCD production development plan

The development plan focuses on achieving CCD production of sufficient quality and quantity to supply the SNAP visible sensors. To this end, we will pursue several paths towards the successful industrialization of the process.

For production of LBNL CCDs we are considering four scenarios:

1. DALSA does front-side processing up to thinning step; LBNL does thinning, ISDP, frontside contact-etch, metallization, and backside ITO.
2. A refractory metal such as TiN is used instead of Al, allowing the contact etch and metallization to be completed at DALSA prior to ISDP. LBNL is responsible for thinning, ISDP and backside AR coating.
3. Working with a traditional CCD vendor to fabricate CCDs using the LBNL technology.
4. LBNL does the entire fabrication on 100 mm wafers.

We now describe the series of activities over the next 24 months we have planned in order to accomplish the above goals.

2.4.4.1 Develop local 150 mm backside finishing processing capability

We have worked with several vendors and qualified one to grind and polish wafers to thicknesses between 200 and 300 μm. We are also exploring a final chemical polishing step to eliminate residual sub-surface damage, if any remains.

The recently installed 150 mm aligner at MSL has been used to finish 150 mm wafers from DALSA (contact etch, metallization, ITO AR coating). In the process we identified shortcomings with our Tegal etcher, specifically in the processing of large format devices. This effect is less noticable on smaller CCDs and may be due to the “antenna effect” caused by the long clocking traces charging up in the plasma etch process. A visit to Tegal did not resolve the issues, and we are now exploring the use of a new etcher recently installed on the Berkeley campus. Purchase of a more modern etcher for the MSL is being explored. Solving these problems and finalizing the backside finishing process steps is presently the most critical area for our CCD R&D program.

2.4.4.2 150 mm SNAP v. 1 CCD

We have ordered 36 wafers at DALSA with a new mask set containing our best effort at the SNAP CCD configuration. This layout is dominated by 4 SNAP CCDs with the following configuration:

- 10.5 μm pixel size
- 3.5k x 3.5k pixel count
- 4-tap readout
- Higher voltage operation mitigation

The layout also contains two versions of a CCD designed for the visible light sensor for the SNAP spectrograph. The lot will undergo several processing splits. Some wafers will be completely processed without thinning and tested under front-side illumination to study HV behavior. Some wafers will be processed with refractory metal (TiN) through the contact etch and metallization step. TiN does not melt in the high-temperature ISDP back-side processing step, unlike Al, allowing DALSA to fully complete the front-side processing prior to thinning. A process split to explore the effects of thinner field oxide is also planned. The layout is compatible with a 150 mm to 100 mm cut down for final finishing with MSL’s established thin CCD process, if required.

Incorporated in the layout of the large format devices are designs to enhance the radiation tolerance and reduce diffusion. These include a layout modification of the p+ guard ring to reduce the possibility of a highly ionizing particle from shorting the substrate voltage power supply across the oxides, and the use of a thinner field oxide to reduce the electric fields in the channel-stop-to-channel and channel-stop-to-bulk regions. The guard ring layout modifications are also designed to produce devices that can be routinely operated at 80 – 100 V to reduce diffusion.

The first batch of wafers has arrived and one is shown in Figure 12. The large devices are the SNAP version 1 prototypes.

2.4.4.3 New 100 mm CCD

One of the designs of the large format devices in Figure 12 will be selected after testing to be produces at MSL on 100 mm wafers.

2.4.4.4 150 mm SNAP v. 2 CCD

There will be a second round of SNAP CCD pre-production. A new layout and mask set may be required, depending on the results of the previous version production.

2.4.5 CCD packaging status and development

Before a CCD can be tested, it must be packaged so that thermal and electrical contact can be made. Packaging development is taking place at LBNL and at Yale University, and we are also working with the University of Arizona Imaging Technology Laboratory to take advantage of their expertise in bump-bonding.

At LBNL, a class 10000 clean room was constructed for packaging CCDs. Additional supporting equipment includes a refrigerator for glue storage, a vacuum oven, a laminar flow bench, and a wire-bonder. There is a dedicated test and measurement facility adjacent to the cleanroom for characterization of devices intended for use at ground-based telescopes and for SNAP pre-production. To ensure high yield and good quality devices, the staff has recently undergone training for ESD protection procedures.

Yale University is experienced in packaging CCDs for astronomical imaging applications, having recently completed the packaging and testing of 112 CCDs for the Palomar QUEST large-area camera. Yale has a class 10,000 cleanroom as well as several dedicated laboratories equipped for sensor packaging and testing, and a staff experienced in precision instrumentation for astronomical applications. Yale recently purchased a dewar and a readout controller for use in SNAP R&D.

Several packaging techniques have been developed. For quick and convenient testing, a window-frame style mount is used in which the CCD is positioned in the center of a cutout in a printed circuit board and wirebonds make the electrical connections. For ground-based astronomy a 4-side abuttable mount has been developed, illustrated in Figure 13. A CCD is glued to a thick AlN substrate that is patterned with electrical traces and contracts. Wire-bonds provide contact between the substrate and the CCD. This is then glued to a molybdenum mounting block containing precision alignment pins. Precise control of the stacked height of the assembly is provided by glue layers and a precision gluing fixture. Experience with this packaging design has taught us to avoid glue lines or vias under the active region of the CCD; these features “print through” to the CCD images, most likely by introduction of stress into the silicon. Figure 14 is an interferograph of the CCD optical surface at 140 K. The peak to valley variation is about 6 μm.

More recently we have been exploring SNAP-specific, 4-side abuttable packaging designs that eliminate wirebonds to the CCD. Instead, the CCD is bump-bonded to and fully supported by an AlN substrate, which in turn is glued to an Invar mounting block. Finite element analysis has demonstrated that these materials are well matched for the minimization of thermally-induced stress in the CCD. This concept is illustrated in Figure 15. The CCD is bump-bonded to the AlN substrate, and the gap is filled with low-viscosity glue. An Invar foot is attached to the AlN substrate. Traces carrying the electrical signals come through vias in the AlN substrate and are routed to a cutout in the center of the Invar foot. (The vias are located on the edge of the AlN, below the guard ring on the CCD.) In the Invar cutout region, a daughter board is mounted and wirebonded to the traces. The daughter board supports connectors, and eventually will host the front-end ASIC.

To qualify the parts and procedures necessary for the SNAP packaging concept described above, we have begun a packaging effort based on the bump-bonding technique for our large format, 2k x 4k devices. These CCDs are well-suited for ground-based astronomical use and the experience is of direct benefit to the development of the packaging for SNAP. To support this packaging effort, we have brought on an experienced technician. From this packaging effort we will develop procedures and yields for production of SNAP parts. In parallel with the 2k x 4k packaging effort we are preceding with design and mechanical prototyping of the SNAP packaging concept targeted at the 3.5 k x 3.5 k SNAP v. 1 CCDs presently in production at DALSA Semiconductor.

The optical prescription of the telescope is being used to develop mechanical placement tolerances for the packaged CCD modules. Control of the SNAP focal plane surface to ±20 μm appears to be achievable since we have obtained package height control of 5 μm at room temperature.

2.4.6 CCD testing results and plans

To support the testing of CCDs, we have in use three sets of dewars, Astronomical Research readout controllers, and SUN workstations at LBNL and another setup at Yale University. We have an ever growing suite of software for the readout controllers and the workstations to support new measurement procedures. One of the LBNL dewars is devoted to testing packaged large-format devices for use in ground-based astronomy, and it will also be used to characterize packaged 3.5 k x 3.5k v. 1 SNAP CCDs. A second is used for diffusion and intrapixel response measurements, and the third dewar is used for routine testing and characterization of devices from new CCD layouts and process variations. In this section we summarize some of the CCD testing results obtained at LBNL and describe our future testing plans. More extensive reporting can be found in the 2002 version of this document in the areas of:

- Dark current
- Read noise
- Pre-irradiaton CTE
- Well capacity
- Linearity
- Persistence
- Source follower FET device characteristics pre and post ^{60}Co irradiation.
- Packaging material radiology.

2.4.6.1 Radiation performance

Traditional astronomical CCDs are sensitive to non-ionizing radiation, such as low energy protons encountered in space, primarily due to degradation of the charge transfer efficiency (CTE). We have an ongoing program to study the degradation of CCDs in a variety of particle beams.

Proton irradiation results

Proton irradiation generates displacement damage in the silicon. Mid-gap levels in the depletion region will contribute to the dark current. Traps in the channel region capture charge carriers during readout and degrade the CTE. We studied two sets of four CCDs that were characterized and then irradiated with 12 and 55 MeV protons at the LBNL 88" Cyclotron.[2] We used our commercially fabricated 512 x 1024, 15 μm pitch CCDs in front-illuminated mode. The four CCDs from each set were irradiated at doses of 5×10^9, 1×10^{10}, 5×10^{10}, and 1×10^{11} protons/cm^2. The irradiation took place while the devices were unpowered and at room temperature. After irradiation, the devices were again characterized to evaluate the performance degradation due to radiation damage.

CTE was determined using an Fe^{55} source to deposit a known quantity of charge and measuring the transferred charge. The measurement was done as a function of temperature, with a 30 kpixel/sec readout rate and an x-ray density of roughly 1/70 per pixel. The pre-irradiation CTE of the devices was 0.999999. In Figure 16 we compare the CTE damage rate of our CCDs with two commercial thin, p-type CCDs that have been characterized in a similar way.[3,4] The loss of CTE in the LBNL CCDs is 8 to 10 times lower than in these devices. For reference, the expected SNAP mission dose for CCDs behind appropriate shielding will be $<10^{10}$ p/cm^2 or $<5\times10^7$ MeV/cm^2.

---

[2] C. J. Bebek, D. E. Groom, S. E. Holland, A. Karchar, W. F. Kolbe, J. Lee, M. E. Levi, N. P. Palaio, B. T. Turko, M. C. Uslenghi, M. T. Wagner, G. Wang "*Proton radiation damage in p-channel CCDs fabricated on high-resistivity silicon*," LBNL-49316, IEEE Trans. Nucl. Sci., Vol. 49, pp. 1221--1225, (June 2002)

[3] L. Cawley, C. Hanley, *WFC3 Detector Characterization Report #1: CCD44 Radiation Test Result*, STScI Instrument Science Report WFC3 2000-05, Oct. 2000

[4] T. Hardy, R. Murowinski, and M.J. Dean, "*Charge transfer efficiency in proton-damaged CCDs*," IEEE Trans. Nucl. Sci. 45(2), pp. 154-163, April 1998.

Conventional CCDs with phosphorus-doped n-channels are susceptible to the generation of phosphorus vacancy (PV) traps during irradiation that degrade the CTE, whereas in p-channel devices the dominant trap is believed to be the divacancy (VV). VV trap formation is considered to be less likely, and the trap energy lies further from the mid-band than PV traps and so should contribute less to the dark current. These are the properties that make p-channel CCDs more radiation resistant.

We have used our parallel and serial CTE measurements at different temperatures, radiation dose and proton energy to identify the degradation mechanism. In addition to the divacancy trap, carbon and oxygen impurities in the n-type silicon can result in C-O or C-C traps. A model has been developed that has only the three trap densities as free parameters; only the VV and CO traps contribute significantly.

Since our CCDs have a much larger depleted volume than conventional CCDs, there was a concern that unacceptable dark current levels might result from radiation damage. Figure 17 shows the measured increase of dark current with radiation dose at fixed temperature. The increased dark current is modest.

<u>*Future irradiation tests*</u>

We plan to carry out radiation tests on cold, powered devices. We believe that our room temperature study of proton generated traps give some insight into the cold temperature results, but the measurements will be performed in any case. This will entail measuring CTE and dark current at 140 K for a few radiation dose levels. Ionizing radiation at cold temperatures can integrate trapped charge in oxide layers more quickly than at room temperature due to different annealing times. We will also measure cold, powered devices at the LBNL ^{60}Co source and look for CTE changes and operating voltage offsets for a few dose levels.

Space radiation consists more of species than protons. We plan make use of the “cocktail” beam at the LBNL 88” Cyclotron and Yale University van de Graff accelerator to study the impact of more heavily ionizing particles.

We are working to understand the flux and probable energy deposition of highly ionizing heavy cosmic rays in shielded CCDs. The GEANT and MARS simulation packages are being used in studies at FNAL to model the interactions of particles with the SNAP instrument and cosmic ray shield, using SPENVIS to model the particle fluences and energy spectra for the SNAP orbit. In addition to computing the total dose at the location of the focal plane and in the warm electronics area, this study will address whether enough localized ionization can occur to cause a fatal discharge of the substrate voltage across a CCD insulating layer.

2.4.6.2 <u>Diffusion</u>

An important parameter in CCD performance is charge diffusion. Diffusion in thick, fully depleted CCDs is a function of the temperature, thickness, wavelength, and depletion voltage. Short wavelength photons convert at the backside of the CCD and the resultant holes drift to the collection well in an electric field generated by the depletion voltage. A hole never sees a field free region and thus has a well defined drift time through the device. During the drift, there will be lateral diffusion which will increase the point spread function. The diffusion is linear in the CCD thickness and goes as the inverse square root of the depletion voltage. For the LBNL CCD technology, a 200 μm thick device depleted at 60 V should have an rms diffusion constant of 4 μm, a good match for a 10.5 μm pixel and the diffraction scale of point objects in SNAP.

We have constructed a pinhole projector with a 2.4 μm FHWM beam that can measure diffusion at this level. Measurements have been carried out at wavelengths from 450 to 650 nm, with a wide range of bias voltages.[5] We use a "virtual knife-edge" technique to measure the point spread function (PSF), illustrated in Figure 18. The CCD is divided into a grid and all of the charge to one side of a given row or column is integrated as the pinhole is stepped across this boundary. The derivative of resulting distribution is a Gaussian at high substrate voltages with rms equal to the diffusion; see Figure 19.

We have performed measurements on a 280 μm thick, 800 x1100 15 μm pixel, back-illuminated device. The diffusion at the maximum substrate voltage of 77 V is measured to be 6.4 ± 0.2 μm, and the dependence on depletion voltage, shown in Figure 20, is in good agreement with theory.

The diffusion measurement program is ongoing, and will be used to characterize the SNAP v. 1 CCDs, which should be operable at voltages exceeding 100V and which we plan to thin to 200 μm. In addition, the pinhole projector will be used to study intrapixel variations, which can occur if the charge that drifts to the collection region encounters distortion due to irregularities in the termination of the drift field. Detailed electrostatic simulations indicate that this should not be a problem. To test this we will scan our pinhole, which is much smaller than the pixel size, across the backside in submicron steps and analyze the distribution of the collected charge.

2.4.6.3 High voltage testing

We have operated LBNL CCDs with depletion voltages of up to 80V and do not observe breakdown. A review of the CCD design indicated that internal fields can be reduced by a factor of two by using a thinner field oxide. A repositioning of the ground guard ring can further isolate the substrate power supply from the channel region. These changes have been implemented in the new CCD layout currently in fabrication at DALSA, and we plan to test the long-term stability of these devices operated between 80 and 100 V.

2.4.6.4 ASIC development support

The development of an integrated circuit for processing the CCD analog signals has progressed well, and we are about to begin the first tests with the correlated double

[5] C. Bebek, A. Karcher, W. Kolbe, D. Maurath,V. Prasad, M. Uslenghi, M. Wagner, "*Measurement of Lateral Charge Diffusion in Thick, Fully Depleted, Back-illuminated CCDs,*" to be submitted to IEEE Trans. Nucl. Sci.

sample CRIC chip interfaced to an LBNL CCD. Clock and bias will be provided by our test lab controllers. A second test is planned for the next iteration of the readout chip, which will combine the correlated double sampler and with an ADC. Again, a test lab controller will provide clocking, bias generating, and data collection. Ultimately, the front-end chip will be packaged together with the CCD and both will be tested together at cryogenic temperatures.

2.4.7 Other visible sensor options

Conservative project management should include backup plans for aspects of the project that are still in an unproven, R&D phase. For this reason, we have selected silicon p-i-n diodes for a limited R&D program as a backup option for the SNAP visible imager. Other CCD technologies were considered, but suffer from several problems including low QE in the red, sensitivity to ionizing radiation in space, and unacceptably large diffusion.

Silicon p-i-n (or “pin”) diodes are a promising new technology with some of the same advantages offered by LBNL CCDs. They are typically constructed on fairly thick (150 - 200 µm) silicon that is fully depleted; this controls diffusion and provides sufficient absorption length for good response in the near-infrared. Radiation tolerance should also be better than conventional CCDs because there is no charge transfer inefficiency. Silicon pin diodes are hybridized to a readout multiplexer, like those used for hybrid near-infrared HgCdTe sensors. This is a potential advantage for SNAP because a common readout could be used for both the visible and near-infrared imagers.

This technology is untried in astronomical imaging and the available pixel sizes are at least a factor of two larger than what is required for the SNAP visible imager. Development of smaller pixels may be possible, but would require R&D on both the sensor and the multiplexer.

We have received a Rockwell Scientific for a 1k x 1k, 18 µm pixel engineering device from their HyVisi silicon pin diode product line. The device is hybridized to their H1RG readout multiplexer. We plan to measure the dark current, read noise and characterize the diffusion at 140 K. We have commissioned and received a study from Rockwell for small pixel development. If the device parameters meet the SNAP scientific requirements, and smaller pixels can be successfully fabricated and hybridized, silicon pin diodes would provide an attractive alternative to the LBNL CCD technology.

2.4.8 CDR planning

A major deliverable at the end of R&D is a cost and schedule for producing fully tested CCDs. From the prototyping runs we will know the foundry production costs and turn-around times and our assembly and test program will measure the yield of usable devices. From these we can establish a fabrication cost and schedule.

The yield of devices will also determine how large a production test facility we will have to construct. Our experience with the R&D test facility will establish the equipment and labor costs required for a production facility.

2.4.9 *Risk assessment*

Preliminary indications are that commercially fabricated LBNL CCDs function well: read noise is low, CTE is high, dark current is low, and radiation tolerance is acceptable. The main risk is selecting a CCD fabrication plan that can deliver SNAP CCDs on time. We have outlined several alternatives, one or more of which should be successful. As a backup we have initiated a limited R&D program to study hybridized silicon pin diodes as an alternative visible imaging technology.

Figure 5. A false color image of the Dumbell Nebula featured on the cover of the NOAO September 2001 newsletter. The background stars are only visible because of the 1 μm wavelength response of our CCDs.

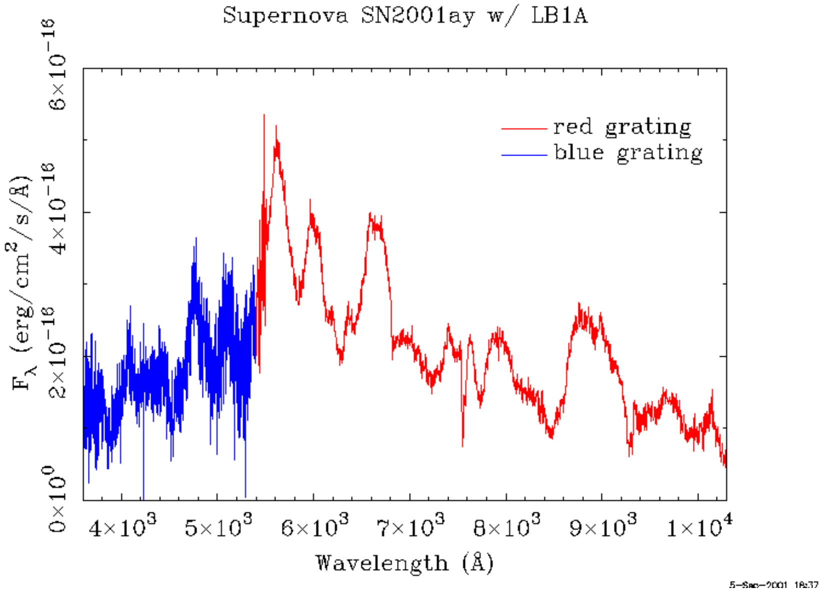

Figure 6. A supernova spectrum acquired by the LBNL Supernova Cosmology Project on the NOAO RC Spectrograph showing the extended response of our CCDs to beyond 1 µm.

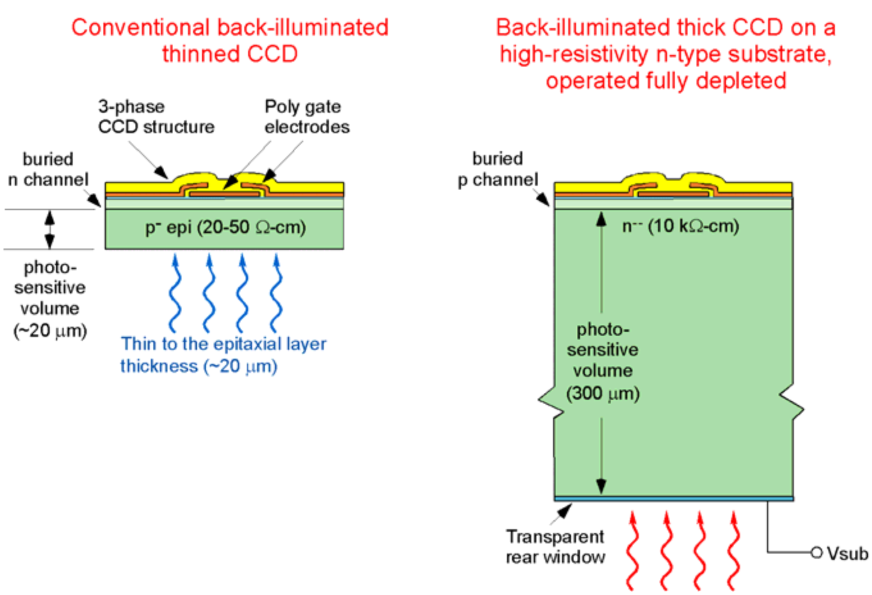

Figure 7. Architecture comparison of a conventional back-illuminated n-channel CCD and an LBNL p-channel CCD.

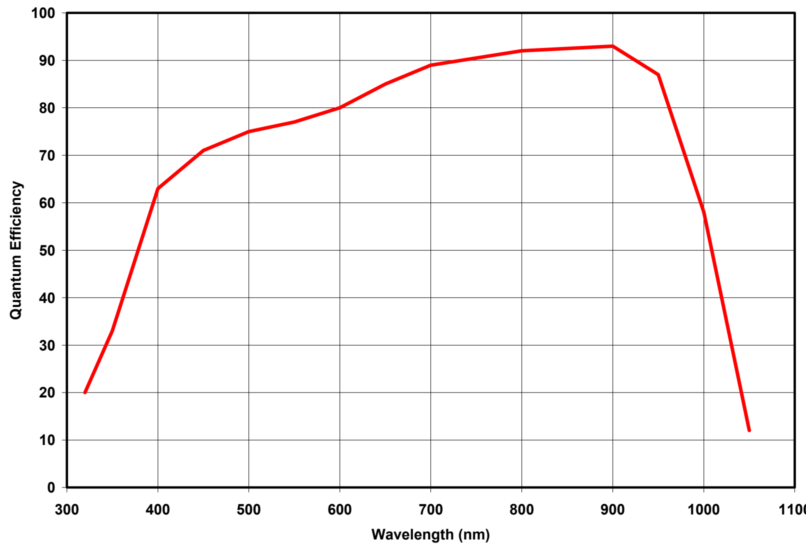

Figure 8. Quantum efficiency of the LBNL CCD.

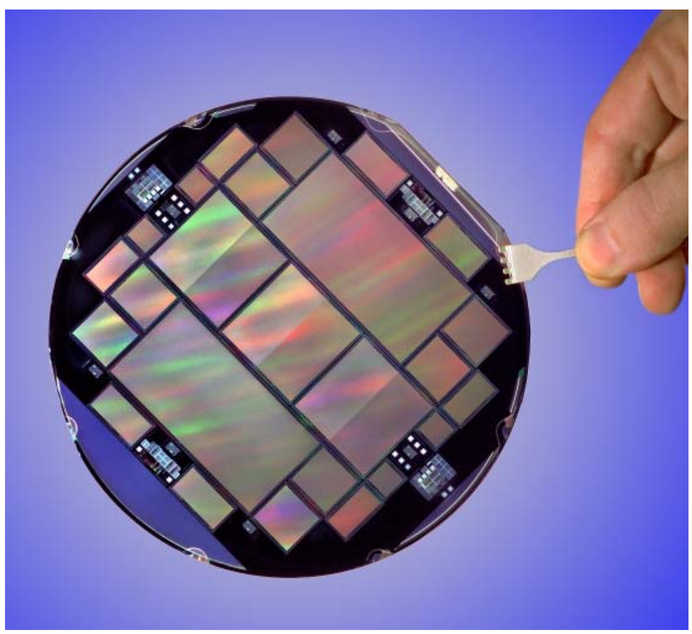

Figure 9. A 150 mm commercially fabricated wafer containing a variety of CCDs. The large rectangles are 2k x 4k, 15 μm CCDs and the large squares are 2880 x 2800, 10.5 μm CCDs.

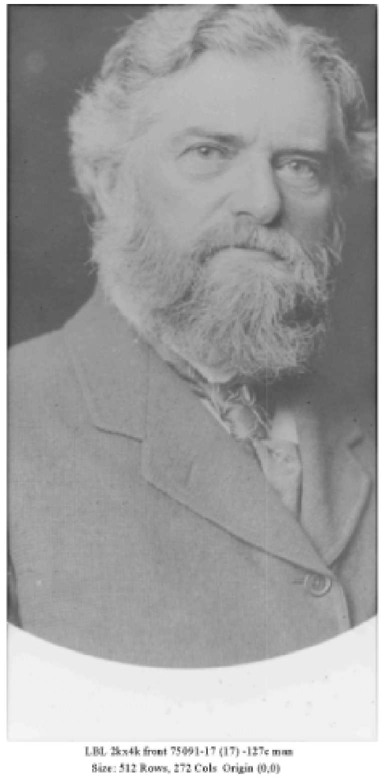

Figure 10. A front side illuminated image taken with one of the 2k x 4k, 15 μm CCDs commercially fabricated.

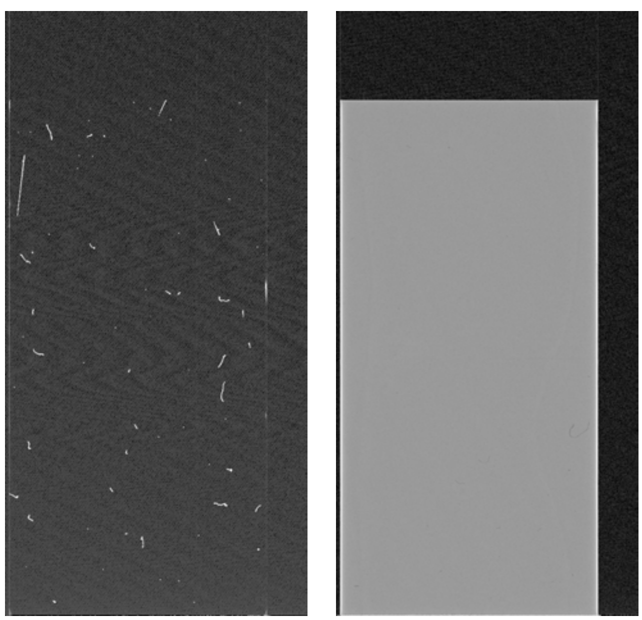

Figure 11. Fully commercially fabricated CCD. The image on the left is a 1000 s dark exposure and the image on the left is a 600 nm flat field

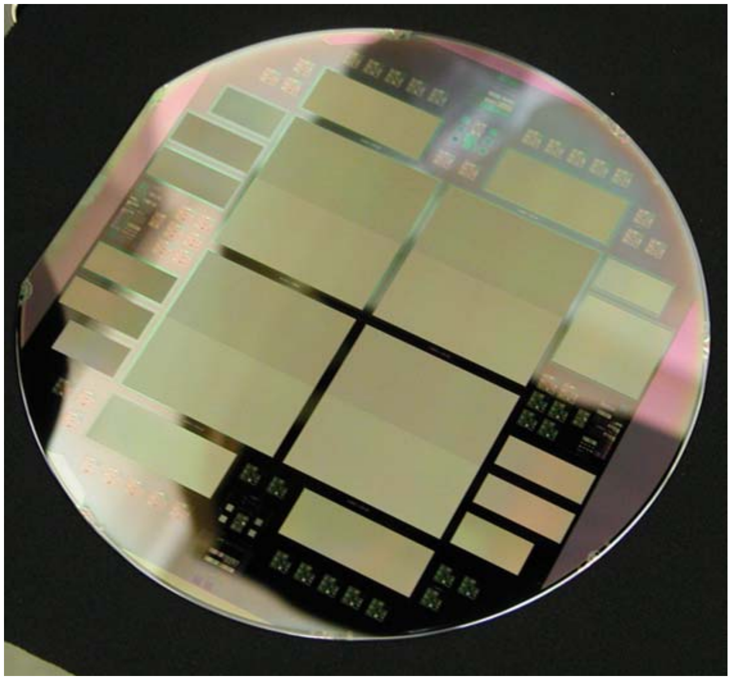

Figure 12. A 150 mm commercially fabricated wafer containing four 3512 x 3512, 10.5 μm SNAP version 1 CCDs.

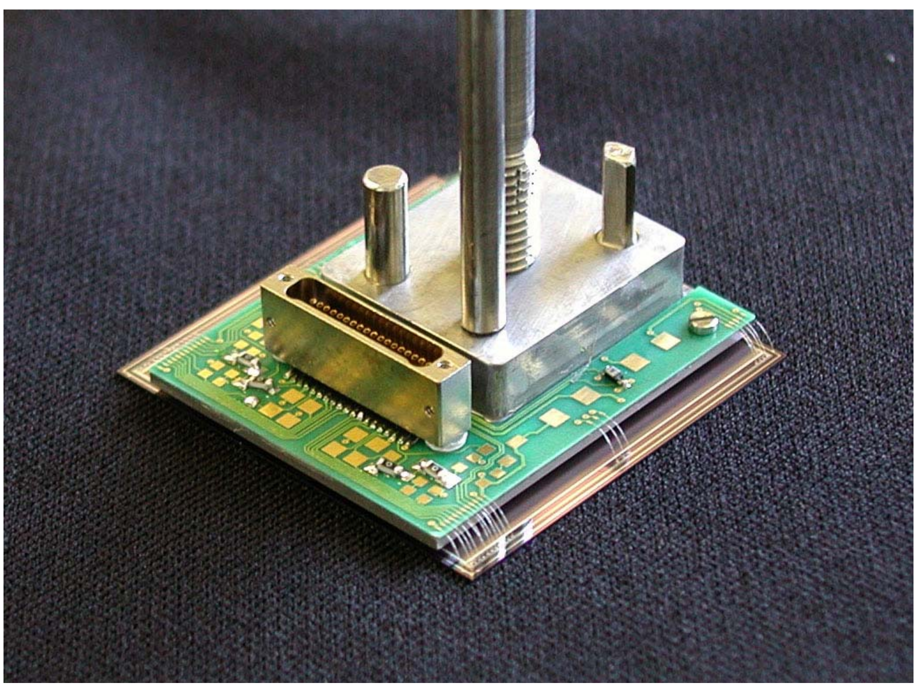

Figure 13. Four-side abuttable packaging developed for front side illuminated CCDs. The CCD is at the bottom of the stack and is glued to a molybdenum mount. A printed circuit board is connected with wire-bonds down to the CCD.

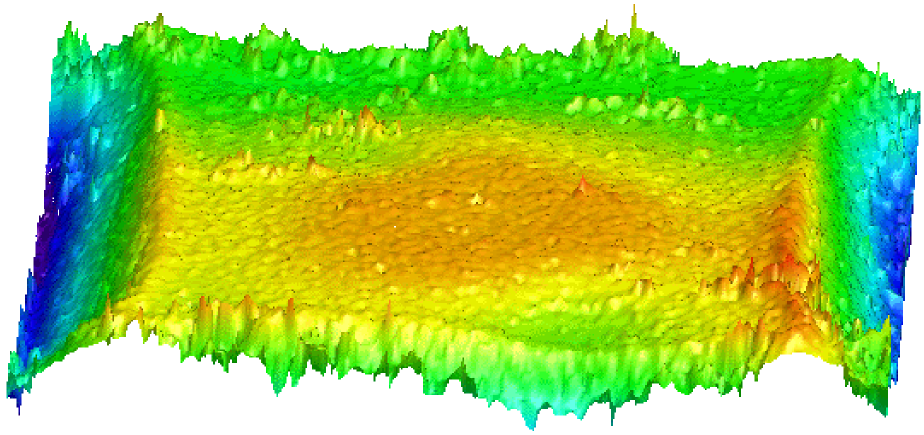

Figure 14. A speckle interferograph at 140 K of the optical surface of the package shown in Figure 13.. The maximum peak to valley excursion is 6 μm.

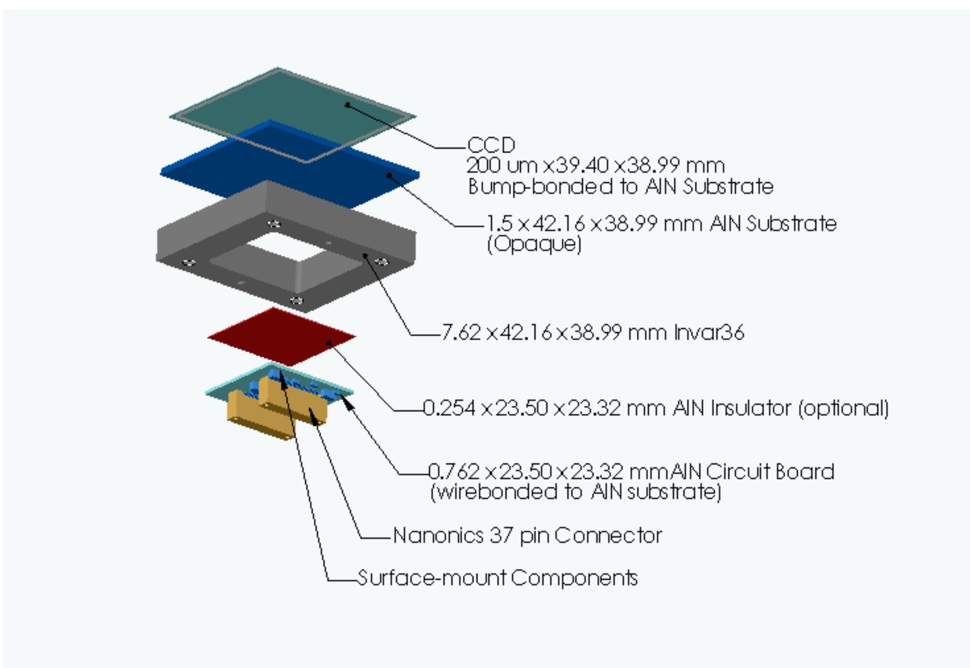

Figure 15. Conceptual design of the 4-side abuttable package for the SNAP v. 1 CCD

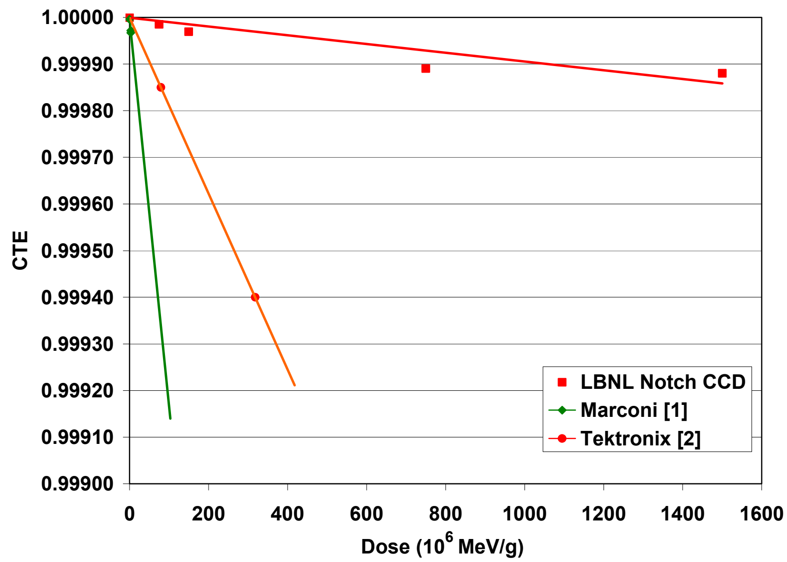

Figure 16. Comparison of LBNL CCD CTE degradation to two conventional n-channel CCDs. Since the doses were done at different proton energies, we convert them to a non-ionizing dose in MeV/g.

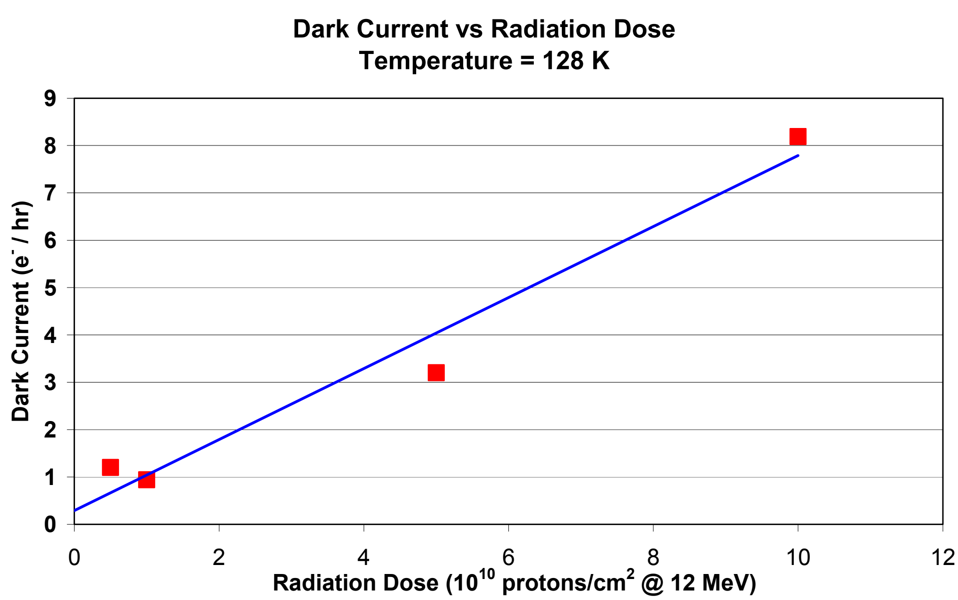

Figure 17. Dark current in electrons per 15 µm pixel per hour as a function of radiation dose.

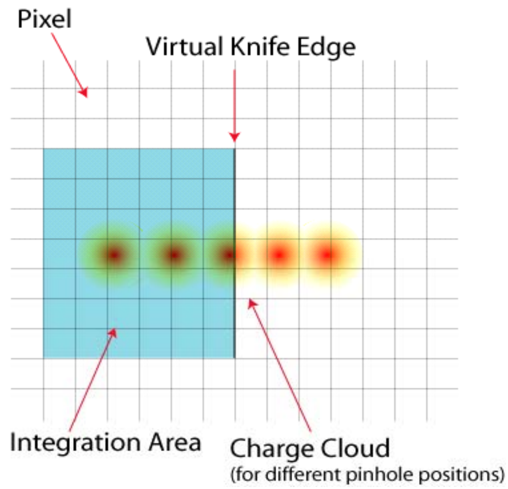

Figure 18. The "virtual knife-edge" technique used to measure the point spread function.

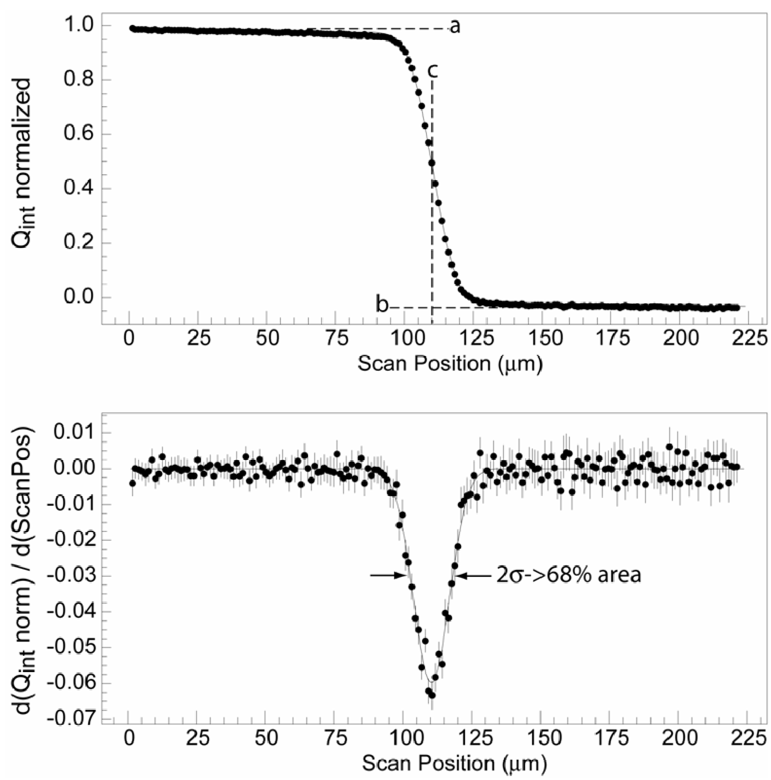

Figure 19. Normalized charge measured as a function of the scan position over the virtual knife edge (top), and the derivative giving the PSF (bottom).

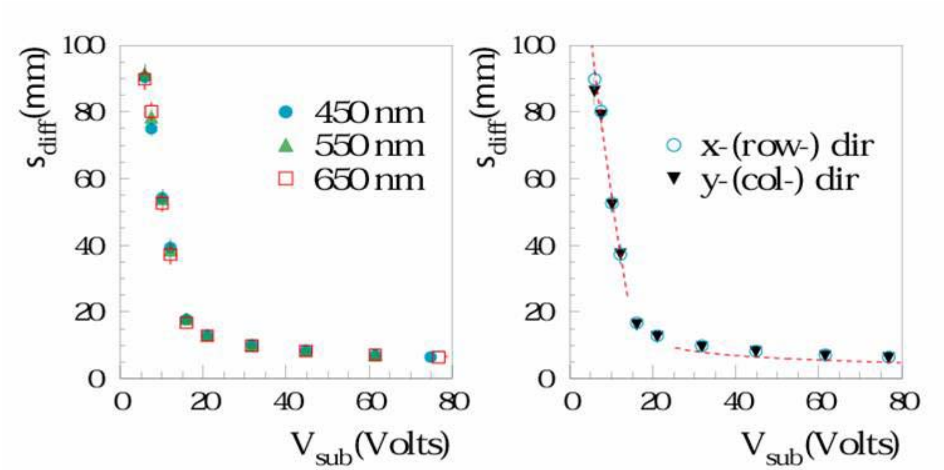

Figure 20. RMS diffusion in microns as a function of bias voltage for 3 different wavelengths (left) and for both row and column directions (right).

2.5 On-Sensor Filter R&D

We are exploring the direct, on-sensor deposition of interference filters for SNAP. Potentially this could eliminate three issues: the mechanical support of discrete filter plates above the sensors, the (correctable) optical distortion due to the thickness of plate filters and their displacement from the sensors, and the internal reflection and scattering of bright sources that might mimic a weak source. The primary goals of this R&D program include:

1. Develop specifications for the SNAP interference filters and demonstrate that these specifications are being met. These include:
   - Transmittance at pass-band center.
   - Maximum allowable change in transmittance versus angle and temperature.
   - Pass-band edge ‘slope’
   - Out-of band transmittance.
   - Optical flatness.
   - Stability to environmental effects.
   - Sample-to-sample uniformity.

2. Demonstrate that the filter deposition process has an acceptable impact on device yields, and on the operating characteristics of the devices. Requirements include:
   - The filter deposition step should exhibit > 90% device yield.
   - Devices passing the filter deposition step should have a negligible increase in readout noise, dark current, cosmetic problems, etc., as a result of filter deposition.

The R&D program will proceed through the following set of steps.

2.5.1 Demonstrate basic proof of principle

Demonstrate basic proof of principle and capabilities of the vendor by depositing an interference filter on a polished silicon substrate, and measuring the reflectance of this filter and the mechanical stresses induced in the wafer as a result of the deposition process. This requires one fabrication run at Barr Associates where a representative filter will be deposited on three of four silicon wafers, with the fourth kept for control. This filter deposition step is already complete; one of the wafers is shown in Figure 21.

2.5.2 Develop provisional filter specifications

Develop provisional filter specifications and perform computer modeling to develop a filter design to meet these specs. The computer modeling will be performed by our group at Indiana University. This step was completed in June 2003 and that design was used in Filter fabrication run #2 (below).

2.5.3 Filter fabrication run #2

Deposit a representative prototype SNAP filter on a number of commercial CCDs. These CCDs will be tested for noise, dark current, etc., before and after deposition. A sufficient number of devices will be coated to determine device yield and the uniformity of coating. In addition, a set of these devices will be subjected to a spacecraft environment to determine stability under environmental variation and over the long term. All aspects of the filter performance will be tested against the specifications provided to the vendor. Prior to this run, trade studies will be conducted to evaluate the chemical compatibility of device and filter materials, and adjust the filter composition accordingly.

One fabrication run at Barr Associates using 6 commercial CCDs has been performed. Pre- and post-deposition measurements have been made, including the investigation of the space environmental effects of vacuum and low temperature. This task was completed in October 2003.

2.5.4 Filter fabrication study

Trade studies will be performed at Barr to determine the optimal coating method for SNAP. Two representative SNAP prototype filter designs (one in the IR and one in the visible) will be developed by Barr design engineers per our specifications. A total of six filter deposition runs will be performed to investigate the feasibility of successfully depositing the two designs by three different coating methods: thermal evaporation, ion assist, and sputtering. Both glass substrates and commercial CCDs will be coated, the former for detailed transmittance vs wavelength measurements and the latter for detection of damage/changes to devices. Barr will conduct stress studies on the filters. Indiana University will conduct pre- and post-deposition measurements of the CCDs and detailed transmittance vs wavelength measurements on the witness samples. Environmental effects of low temperature and vacuum will also be studied at IU.

2.5.5 Filter masking study

Barr Associates will perform a trade study to determine the best method of masking CCDs for depositing four quadrant (“checkerboard”) filters. The goal is to minimize the dead zone between filters without damaging the devices in the process. Both photolithography and mechanical masking will be investigated. The filter design will be a SNAP prototype band. The optimal deposition method(s) discovered in the previous activity (2.5.4) will be used for this study. Polished silicon wafers will be coated, along with glass substrates witness samples. Indiana University will characterize the substrates before, during, and after masking and deposition. Between two and four filter deposition runs will be required.

2.5.6 CCD coating study

The most critical element of this R&D effort is to determine if coating active devices (CCDs and HgCdTe) will irreparably alter their performance. Barr Associates will deposit a SNAP visible filter design on an LBNL CCD to verify feasibility. If multiple coating methods from the previous two studies are still viable, multiple coating runs will be executed. Indiana University will study the device(s) before and after deposition to detect any changes the process will induce. If intermediate masking and coating steps are required, we will make measurements after these steps as well.

2.5.7 HgCdTe filter deposition run

Barr and Associates will deposit a SNAP IR filter design on a HgCdTe device to verify feasibility. Indiana University will study the device before and after deposition to detect any changes the process will induce. Knowledge gained from earlier depositions on CCDs (2.5.3 – 2.5.5) will be applied to maximize the chances of success.

2.5.8 Risk assessment

The present concept of the SNAP CCD deployment is that each CCD would have four filters in a 2×2 array and a single filter on HgCdTe. As each sequential step in this R&D program is completed, alternate plans/studies will be initiated as necessary. This could involve altering, adding, or even eliminating tasks previously planned. For example, if the direct deposition of filters is successful but multiple filter deposition found to be problematic, reconsideration of the CCD size would be required to take advantage of this technology. Also, it may be challenging to validate the direct deposition of filters on HgCdTe devices, since these are expensive parts. If either issue were to prove daunting, one could fall back on a traditional, albeit non-trivial, solution consisting of mounting discrete filters over the sensors.

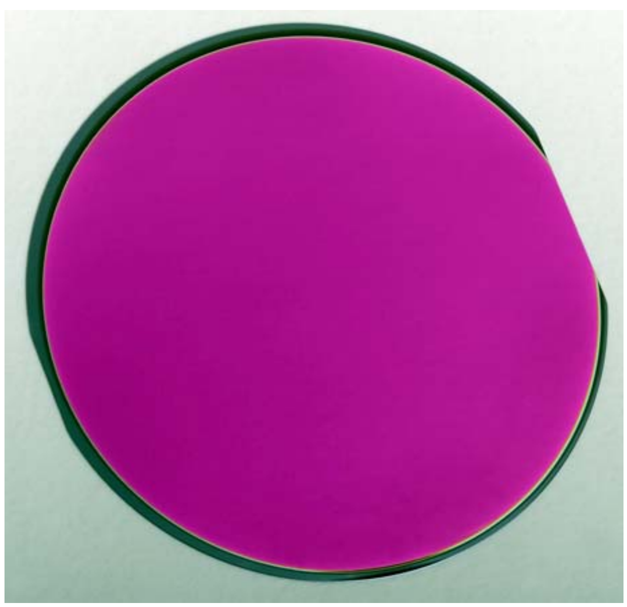

Figure 21. Reflected light from a B-band interference filter directly deposited on an indium-tin-oxide-coated 100 mm silicon wafer.

2.6 Spectrograph

The SNAP spectrograph is required to identify Type Ia supernovae and to correct their peak luminosity. The SNAP flight plan budgets time for a spectrum of each SN candidate at peak to confirm it is a Type Ia. A spectrum also provides the best tool to understand the details of the SN composition, allowing for corrections to the magnitude if needed. The spectrograph is also an important tool for a precise spectrophotometric calibration.

2.6.1 Requirements

To identify SNe Ia up to a redshift of 1.7 within the time constraints of the SNAP flight plan, the spectrograph must have high throughput and broad wavelength coverage. In addition, the capability to simultaneously measure the spectra of a SN and its host galaxy would be a significant benefit: the galaxy subtraction would be simplified and the galaxy redshift can be determined in most cases. Requirements on the pointing accuracy and on the calibration will also be critical parameters for a space application.

Thanks to the broad SN identifying features, a spectrograph with a low spectral resolution is accurate enough for this application, and will be optimized for a flat resolution $\lambda/\delta\lambda$ over the full wavelength range. SN models indicate that parameters such as temperature, velocity or progenitor metallicity, which are directly correlated to the magnitude, can be extracted from the shape of the spectrum. The exposure time is optimized for a specified accuracy on these key parameters at the highest redshift. This leads to a spectral resolution requirement of $\lambda/\delta\lambda \approx 100$, under sampled at one pixel per resolution element. A dithering in the spectral direction will be implemented to recover the optimal sampling if needed. A detector with very low noise in the visible is required to optimize the metallicity measurement, which depends on features in the UV. Finally, to measure the galaxy spectra together with the SN, a field of view of 3" is required with a spatial resolution of 0.15"; this is small enough to cover the SN, while keeping the background contribution low.

These requirements lead to the baseline specifications shown in Table 5.

Table 5. Spectrograph main characteristics

Item	Visible	IR
Wavelength coverage μm	0.35-0.98	0.98-1.7
Field of view	3.0" x 3.0"	3.0" x 3.0"
Spatial resolution element (arcsec)	0.15	0.15
Spectral resolution, $\delta\lambda/\lambda$	100	100
Cumulative throughput	52 %	45%

2.6.2 Instrument concept

An in-depth analysis of different spectrograph designs and an exploration of alternatives have been performed. The outcome of this trade-off study is the selection of an integral field spectrograph based on a reflective image slicer as the best possible design for SNAP.

Integral field spectroscopy is now a mature technique and has been used in many ground based instruments, with the latest generation being developed for 8-meter telescopes like Gemini and VLT (see e.g., Bacon et al., 1999; Le Fèvre et al., 2000; Davies et al., 1998). The principle is simple: take spectra of each resolution element in a contiguous sky area. In this way it is possible to reconstruct a 3D image on the sky (x,y,λ). We can measure at the same time the spectrum of the SNe candidate and that of the host galaxy, without slit losses and without stringent requirements on the pointing capabilities of the spacecraft.

The proposed technical solution for this integral field spectrograph is based on a slicer unit (e.g., NGST IFMOS study, Le Fèvre et al., 1999, ASP conference series, Volume 207, 313). The basic principle is identified in Figure 22: the 2-D field of interest is "sliced" in several strips, with the slices rearranged to enter the spectrograph as the equivalent of one single long slit. This concept has several major advantages compared to a long slit spectrograph. All resolved spatial elements of a contiguous area on the sky have spectra taken; there are no slit losses; and the telescope pointing is relaxed to a fraction of the observed field, rather than being constrained to a fraction of a slit width, allowing for quick acquisition.

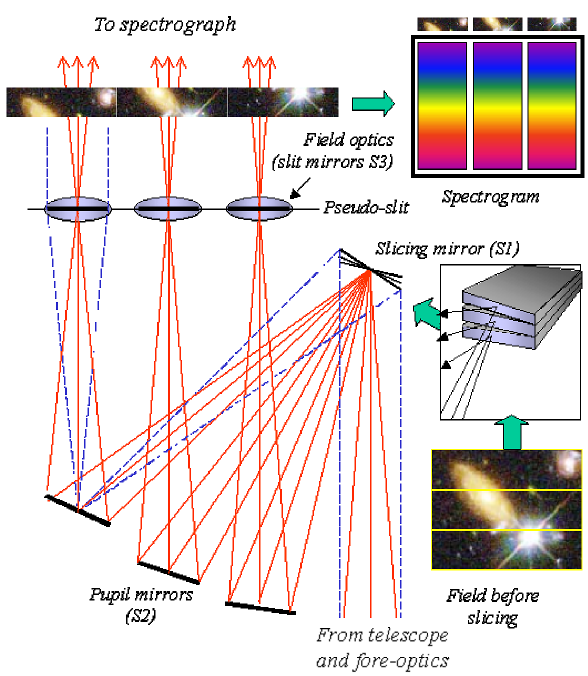

Figure 22. Image slicer principle (courtesy J. Allington-Smith, Durham U.).

The instrument functionalities to be developed are summarized in the instrument block diagram shown in Figure 23. Principal components are described below.

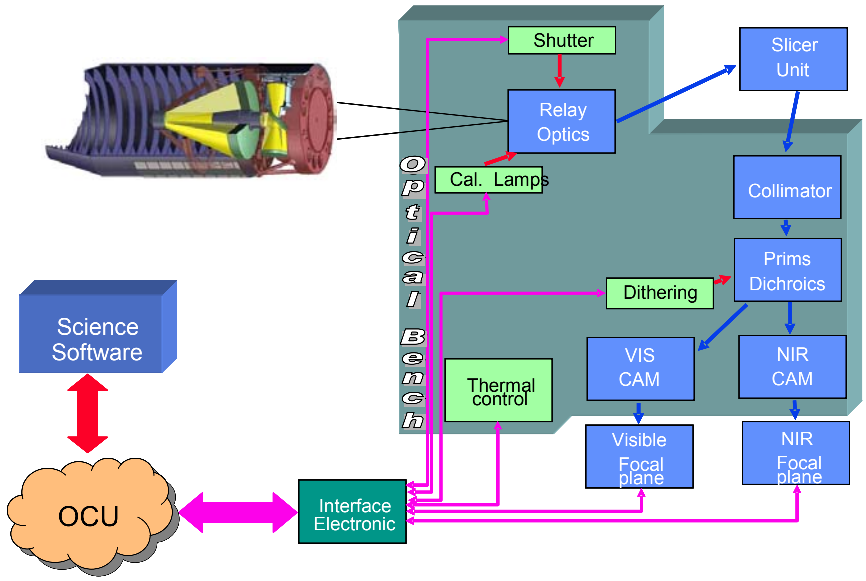

Figure 23. Instrument Block Diagram

2.6.2.1 Relay optics

This unit is the interface between the telescope beam and the instrument. The optical solution is highly dependent on the implementation of the instrument. The definition of this optical system requires the knowledge of the spectrograph position with respect to the telescope focal plane. The beam can be picked off wherever it is most convenient for the overall instrument. It will be beneficial to correct some telescope aberrations (e.g., astigmatism) within this optical system.

2.6.2.2 Slicer unit

The slicer unit acts as a field reformatter. The principle is to slice a 2-D field of view in long strips and optically align all the strips to a long spectrograph entrance slit. The slicing mirror comprises a stack of slicers. Each slicer has an optically active spherical surface on the first edge (see Figure 24). A line of "pupil" mirrors reformats the image, each mirror sending the beam to a slit mirror for the pupil adaptation to the entrance of the spectrograph.

The long, thin, active surface of each individual slicer will produce a large diffraction effect. To minimize flux loses to a few percent, the spectrograph entrance pupil has to be oversized. A combined theoretical and experimental approach is underway at LAM to define the optimum entrance pupil. The baseline requirements on the slicer unit are a positioning accuracy of $\lambda/10$ rms for the optical surfaces and a surface roughness of 5 nm rms (existing prototypes are fully compliant with these numbers).

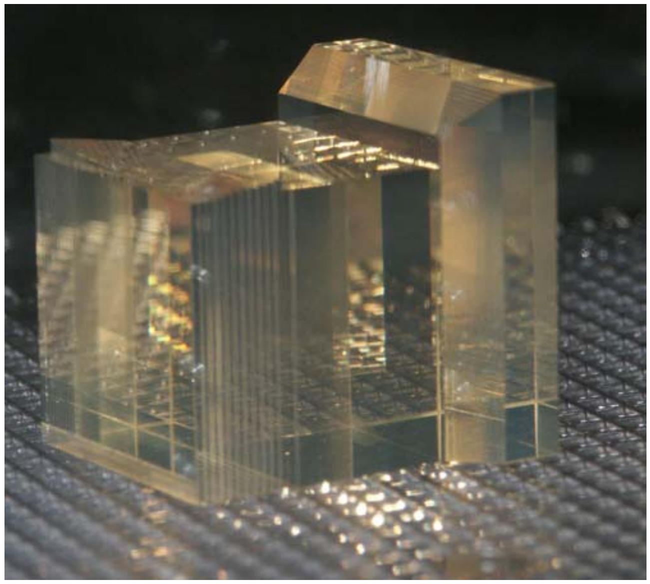

Figure 24. Picture of a block of slices

2.6.2.3 Optical bench

Thanks to the low beam aperture and field-of-view, the spectrograph optics will be straightforward. The actual baseline is classical, and comprises one collimator mirror, one prism with a dichroic and two cameras. Spherical shapes for all the mirrors will provide sharp enough image quality, but by using aspherical mirrors it becomes possible to have a very compact spectrograph. The prism solution is adapted to a flat resolution on the whole wavelength range. The dichroic allows coverage of the two channels simultaneously, one for the visible (e.g., 0.3-0.98 μm) and one for the infrared (0.98-1.7 μm).

2.6.2.4 Focal planes

The two focal planes will be designed around the visible and IR detectors. In the visible, the main goals are high QE and very low noise: given concerns over degradation due to radiation exposure and the poor performance of thinned CCDs in the red part of the visible, we will perform studies looking at the suitability of LBNL CCDs. Thinned, backside-illuminated low-noise CCDs with 1024x1024 pixels will be the alternative option. For the IR, some factors limit the choice of detector technologies: the overall temperature for the SNAP instruments will be fixed in the range 120 -140 K. The spectrograph has to operate in this range. The cut-off wavelength of the array needs to be as close as possible to 1.7 μm, while keeping noise figures low. A 1024x1024, 18.5 μm pixel HgCdTe array from Rockwell is under consideration. The possibility of working at a slightly lower temperature 100 -120 K will be investigated if there is a significant benefit in detector performance, particularly in dark current which will dominate the noise for long exposures of high redshift SNe.

The choice and evaluation of visible and IR detectors will be performed in France, maintaining a strong connection with the teams involved in the characterizing sensors for the imager in order to achieve the simplest solution for SNAP.

Details of the detector performance specifications are given in Table 6. To achieve the quoted performance on read noise and dark current, a multi-sampling technique is required. The impact of the rate of cosmic rays on the readout noise is under study to optimize exposure time and readout techniques.

Table 6. Detector specifications

	Visible	IR
Detector size	1kx1k	1kx1k
Pixel size	10-15 μm	18.5 μm
Detector temperature (K)	140	140
QE (%)	>80	>70
Read noise (e)	2	5
Dark current (e/pixel/s)	0.001	0.02

2.6.3 Summary of spectrograph parameters

The specifications for each spectrograph element are summarized in Table 7. To avoid single point failure, the detectors will be duplicated for reliability. Two detectors will be mounted in each focal plane. The field of view has been enlarged to 3” x 6” and the number of slices required is 40. This does not imply any change in the spectrograph optics.

Table 7. Spectrograph system parameters

	Visible	NIR	System description
Spatial resolution (arcsec)	0.15		2x20 Slices 0.9 x 18 mm
Field-of-View (arcsec^2)	3 x 3		3 x 6
Wavelength (μm)	0.35-1.0	1.0-1.7	Dichroic
Spectral Resolution	100-200	70-100	Prism
Detector Size	1kx1k	1kx1k	800 x 200 useful 2 abutted detectors
Pixel size	10-20 μm	18 μm	Camera F/D=12
Detector Temp (K)	140	140	Passive cooling
Function	Dithering Calibration		Dithering unit Shutter unit Lamp unit

2.6.4 Instrument design

During the past year a pre-conceptual spectrograph design has been developed and preliminary performances studied. A second iteration with more precise requirements will be done next year.

2.6.4.1 Optical design

The optics has been designed to minimize the number of mirrors. This will reduce the risk but will slightly degrade the image quality. A solution with 7 mirrors is currently presented which fulfils a first volume allocation. The optical beam then reaches a BK7 prism with its back face coated with a dichroic. Visible radiation will be reflected, while infrared radiation will continue to a second prism, in CaF2 this time. The BK7 prism is used in double pass in the optical domain to reach the required dispersion with a smaller prism. The NIR beam is dispersed by the CAF2 prism in a double pass at the required R~100. Each beam enters an appropriate camera that images the spectrum on the visible detector on one side and the NIR on the other side.

Figure 25 shows the optical layout. Spatial dithering occurs randomly through small changes due to the pointing accuracy. To implement a controlled spectral dithering, a simple solution can be realized by moving the prism between two fixed positions by an actuator. This is under evaluation and should not be technically difficult.

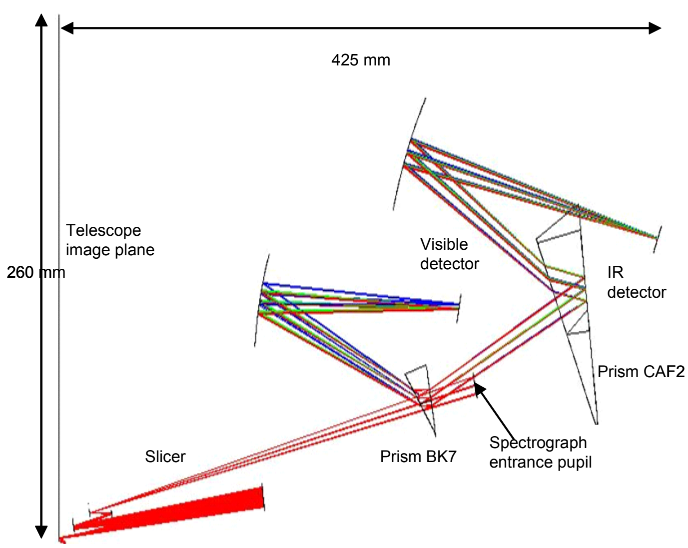

Figure 25. The optical design of the instrument

Figure 26 shows the implementation of the spectrograph optics and the interface with the SNAP telescope. The figure shows that the entrance point to the spectrograph is at the border of the dark zone (the interior cone in the imaging camera). The instrument itself stands behind the large telescope imaging plane at the central place. This configuration allows the spectrograph to be located away from the region occupied by the imaging detector and its associated electronics.

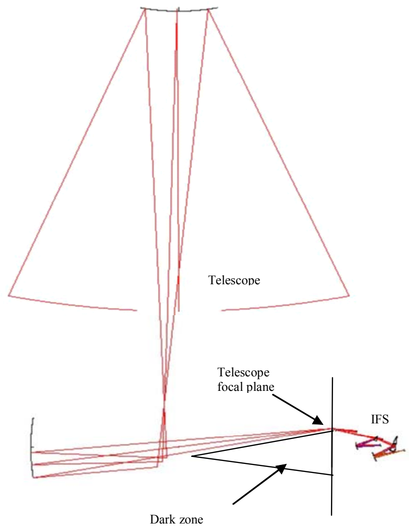

Figure 26. Spectrograph Implementation.

2.6.4.2 Optical performance

The current design meets the requirements on image quality. Figure 27 shows that it is diffraction-limited at 1.7 µm. Simulation work is currently in progress to provide new, refined requirements. The first results suggest that the design will also satisfy the next iteration in the requirements.

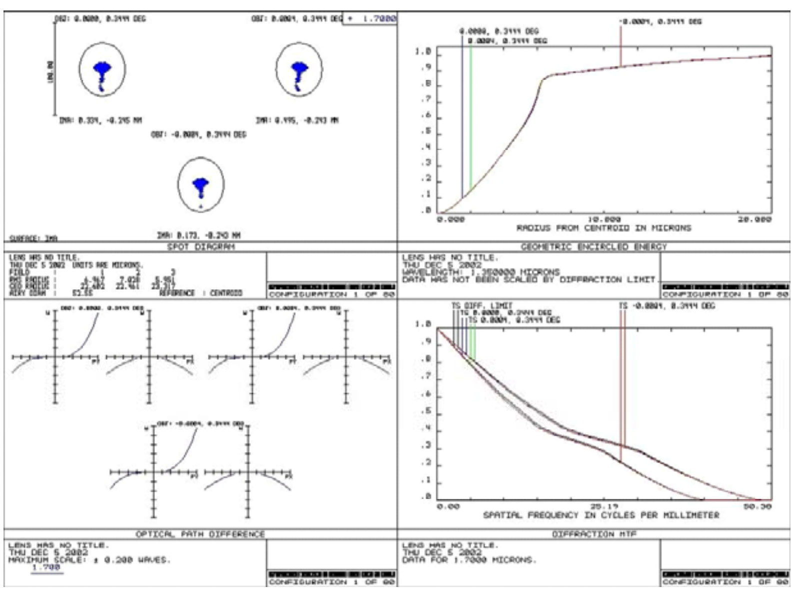

Figure 27. Image quality at 1.7 µm.

2.6.4.3 Mechanical and structural design

Figure 28 shows a first implementation concept for the mechanical structure of the spectrograph.

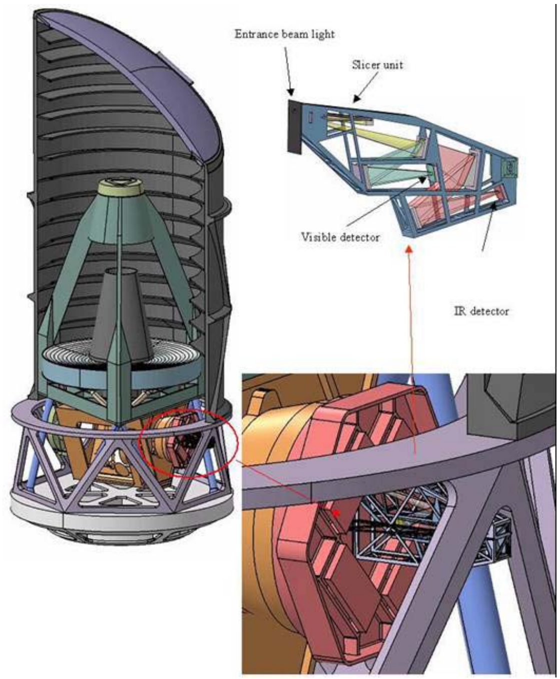

Figure 28. Implementation study.

The choice of the material for the support structure will be determined by its density, rigidity, thermal conductivity, ease of fabrication and compatibility with other focal plane materials. A trade study will be carried out; some of the materials under consideration are listed in Table 8 together with their characteristics. The unquantifiable criteria are noted from A to D (A = excellent). The selection of the best material will take place beginning in 2004 with the design of the structure.

Table 8. Material trade study.

	Zérodur	**Invar**	**Sic**	**Mo**	**Al (alloy)**	**Be**
Young modulus	70 000	210 000	311 000	330 000	70 000	300 000
Density	2.2	8.1	2.9	10.2	2.7	1.9
CTE @ 300K	0.03	1.4	2.6	5.1	24	12
CTE @ 30 K	-0.7	0.3			1.5	0.1
Thermal cond @ 300K	1.3	13.5	156	138	150	180
Manufacturing	B	A	C	B	A	B
Machining	B	A	B	B	A	C
Cost	B	B	B	B	A	C

The structures that will be used to adjust and clamp all the optical elements must also be designed, taking into account the material used for the optical elements and the thermal environment. The experience acquired in the prototype study for the slicer spectrometer for ESA is relevant. For this spectrometer we have developed an adjusting system by using a coordinate measuring machine, and a process of clamping with "floppy" elements.

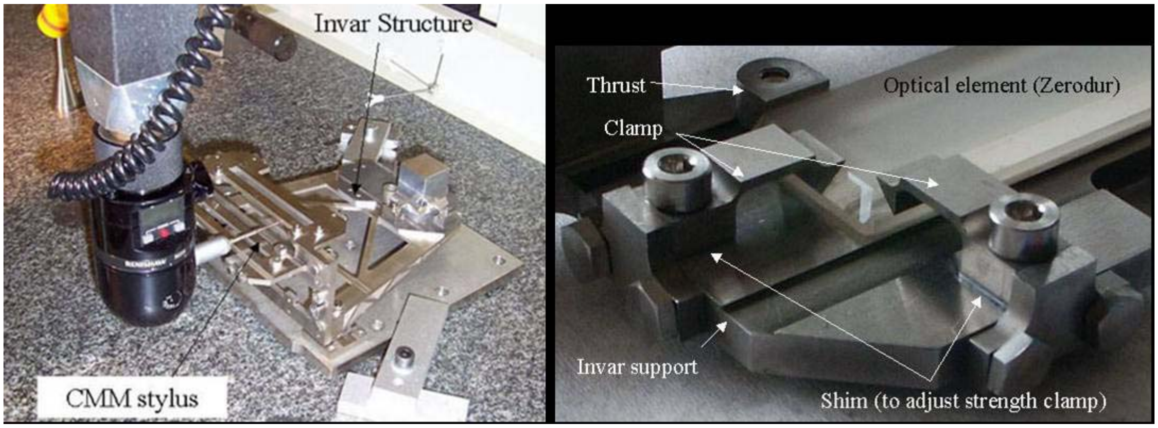

Figure 29. Example of opto-mount clamping and the associated metrology.

2.6.4.4 <u>Mechanical interface with the spacecraft</u>

The mounting of the spectrometer on the main focal plane structure should utilize a kinematic three-point mount, to avoid problems of thermal expansion. However, a thermal coupling is also necessary. Figure 30 illustrates the philosophy of the kinematic three-point mount.

The volume and position of the spectrometer is defined in the interface control document. The optical baffling will be studied. Radiation protection will be provided by the SNAP focal plane radiation shield, but to avoid secondary particles, a specific protection can be envisaged for spectrograph detectors.

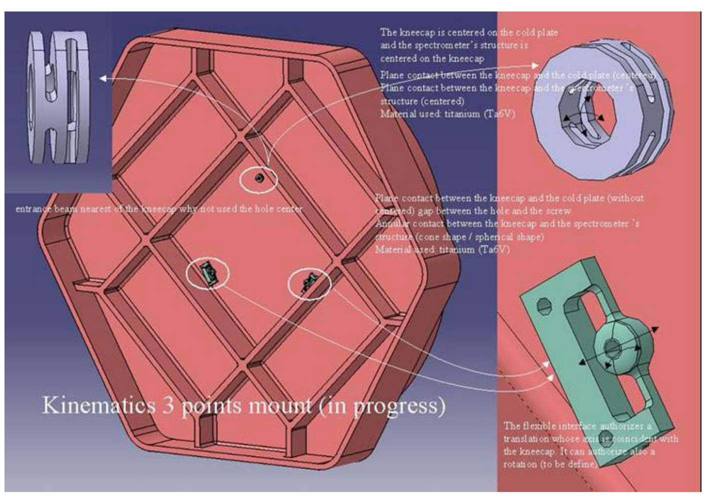

Figure 30. Kinematic mount concept.

2.6.4.5 Thermal and dynamic analysis

A thermo-elastic numerical analysis will be performed on the mechanical elements of the spectrograph. It will be necessary to analyze the behavior of the structure with changing temperature, and to verify, for example, the stability of the optical elements.

Analyses (static, modal, and answer dynamics) will be made to guarantee the behaviour of the structure and the clamping system of the optical elements. Tests shall be realized (sine low level, sine qualification, and random) in agreement with the requirement. They will verify the exactness of analyses.

2.6.4.6 Spectrograph Focal Plane Design

A focal plane definition for the spectrograph sensors has to be developed in the next two years to define the readout electronics and prepare the thermal and mechanical concept. To follow the requirement on reliability, a concept realizing two detectors has been defined and is shown on Figure 31. To allow the readout of the IR and the visible detector data at the same time, a frame transfer is preferred for the CCD detector. This also allows for the possibility of an electronic shutter for calibration purpose.

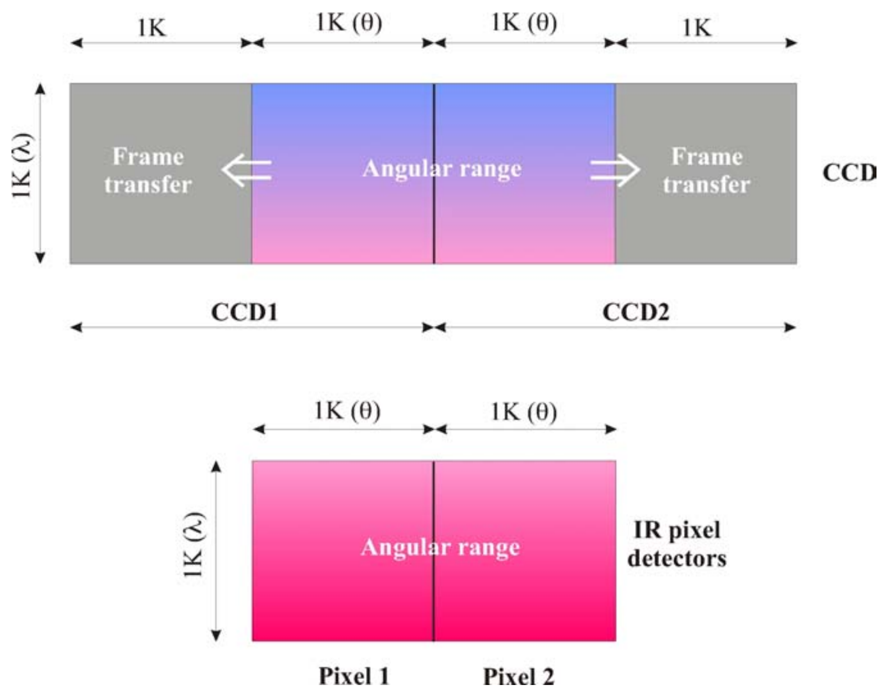

Figure 31. Dual detector definition

2.6.5 Calibration

We have produced a first calibration-oriented performance requirement document, which sets the requirements on three of the major calibration procedures of the instrument, namely the flat-field, wavelength and absolute spectrophotometric calibrations. It is shown that wavelength calibration must have an accuracy of 20 A and that the relative spectrophotometric accuracy of the hardware must be 1% between the blue and red end of the spectra. The baseline calibration procedure is very similar to the one routinely used in long-slit spectrographs. The main steps are:

- Apply detector calibration procedures (may include cosmic-ray rejection)
- Apply flat-field calibration procedure
- Correct for optical distortion of the spectra
- Apply wavelength calibration procedure (may be merged with previous step)
- Apply absolute spectrophotometric calibration procedure (note that this step also corrects for residual slope introduced during the flat-field calibration procedure)

We can already give a preliminary list of what would be needed to calibrate the spectrograph (a more accurate list will be available once the detailed calibration error budgets are established):

- Continuum lamp with uniform illumination over the field of view of the spectrograph (could be the lamps used for the flat-fielding of the imager).
- Emission-line lamps with lines distributed over the complete spectral range (for the wavelength calibration)
- Small-step dithering capability at observatory level for spectral point-spread function stability (to average out the so-called slit effect).
- At instrument level, it might be necessary to implement spectral dithering (by mechanically tilting the prism)
- Set of spectrophotometric standard stars for the absolute flux calibration of the instrument.
- Possible need for a mechanical or electronic shutter (i.e., employing frame transfer into an unexposed part of the detector) to allow short exposure times on bright calibration stars.

2.6.6 Software development

A full simulation of the optical system has been developed, based on Fourier optics. It is coupled to the detailed design of the instrument via Zernike coefficients produced by the Zemax program. The output is a discrete PSF at the detector level, for a monochromatic point source at a given position.

It has been used to simulate a complete SN spectrum in the 0.35-1.7 μm range (see Figure 32), and to verify that the expected performance can be reached. Spectral resolution and spectrograph plus telescope throughput have been verified.

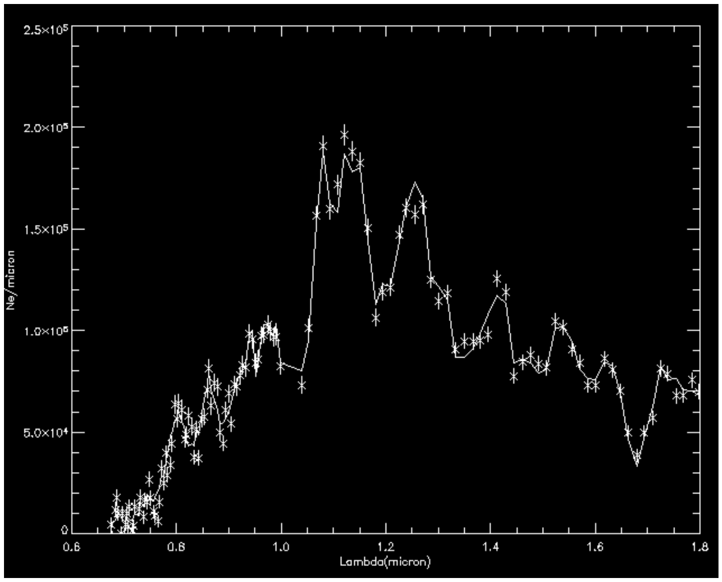

Figure 32. Simulated calibrated spectrum.

This approach is not practical for more extensive studies, because of the large variety of discrete PSF representations needed. To solve this problem, a parameterization based on a shapelet decomposition of the PSF is currently developed. First results show that the required accuracy can be reached with a limited number of eigenfunctions. CPU time necessary for the reconstruction is manageable and the volume of data is now very small. We have written a Java implementation of the shapelets library (A.Refregier, R. Massey).

2.6.7 Performance

2.6.7.1 Spectral resolution

The spectral resolution is shown in Figure 33 and has been optimized to be as flat as possible. The detailed simulation has been used to confirm this resolution.

2.6.7.2 Throughput

The estimated throughput of the instrument is given in Table 9. Thanks to the good throughput of the reflective silver-coated optics and to the slicer performance, the expected total throughput of the instrument is 3 to 4 time higher than that of the HST-STIS. To derive this table, the full simulation of the slicer and the spectrograph has been used including the diffraction and aberration effects on each optical plane.

2.6.8 Risk assessment

Our preliminary analysis indicates that the image slicer and the detectors are the only components requiring effort during the R&D phase to mitigate risk later in the project. All other components are well within the current technology.

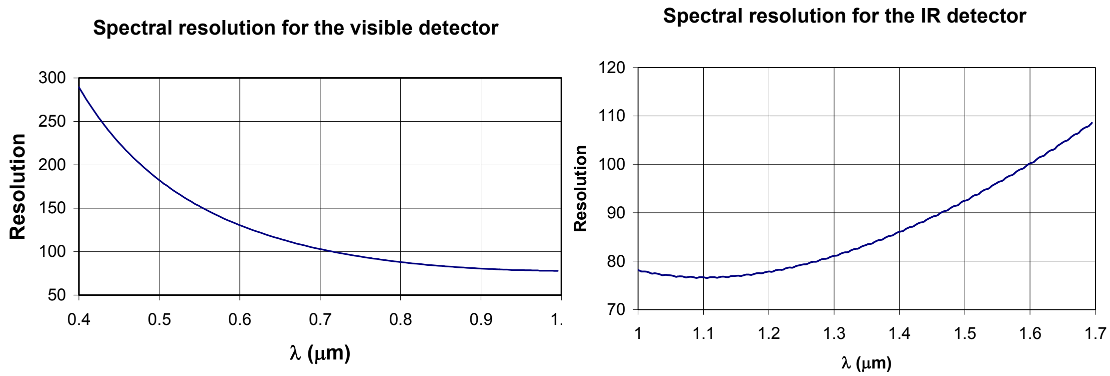

Figure 33. Spectral resolution in the visible (left) and in the NIR (right).

Table 9. Instrument efficiency estimation

	# elements	Efficiency /elements	Cumulative efficiency
Telescope	4	0.98	0.92
Relay optic	1	0.98	0.90
Slicer (mirrors+straylight+diffraction)		0.82	0.71
Spectro	Mirrors 2 Prism Dichroic	0.98 0.81 0.95	0.57
Detector visible	1	0.9	0.52
Detector NIR	1	0.8	0.42

2.6.9 Instrument development road map

After a trade-off study, a pre-conceptual design has been developed which has been used to prove the feasibility and the adaptation of this technique to the SNAP mission. The detailed simulation which is under development has been used to prove the high level performances of the optical system. High level requirements have to be finalized based on the science specifications.

2.6.9.1 Concept development

Figure 34 shows the instrument development roadmap. The detailed technical requirements are under study and will be finalized in the next year, taking into account the simulation results and the calibration studies. Preliminary interface definitions have been set (ICD 00026-MW02-A2003-09-16) and will be pursued in the next months. A new instrumental concept will be designed. The main technical change will be a new definition of the allocated envelope for the spectrograph itself. A new envelope which is shorter than the previous one is proposed, but no difficulties are foreseen, as this can be accommodated with the addition of one mirror in the spectrograph optics.

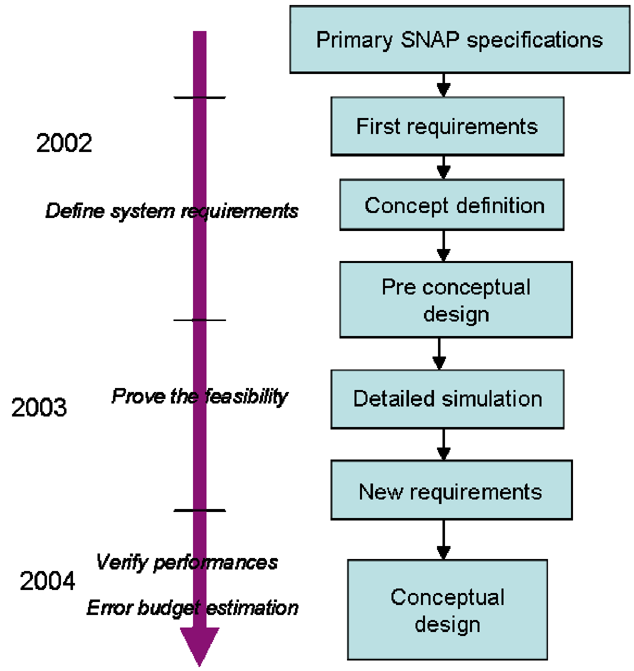

Figure 34. Spectrograph development roadmap

2.6.9.2 Software development

A full implementation of the spectrometer simulation will be pursued. A parameterization of the shapelet coefficients as a function of spatial position and wavelength will be established. The combination with the shapelet decomposition of galaxies will be explored, in order to simulate realistic data cubes for a SN and its companion. The development of the data reduction procedure will start. We expect that it will continue during several years. We will rely on the work of the EUro3D consortium, which develops general-purpose utilities for integral field spectrometers. Customization to SNAP will nevertheless require significant efforts. The precise and detailed simulation of the instrument and associated physics analyses will validate the final design at the end of the R&D phase.

2.6.9.3 Calibration

Calibration strategy will be further developed: we will detail each of the calibration procedures and build the corresponding error budgets. We will then define calibration scenarios (on-the-ground calibration prior to launch; initial calibration campaign immediately after launch; routine calibration sequences) and derive stability requirements for the instrument and observatory (feed-back to the opto-mechanical design). These detailed calibration scenarios will be used as inputs to the operation of the instrument, in particular to estimate the operational efficiency of the instrument.

2.6.10 R&D activities

Two main activities have been identified as R&D studies for the two next years: one on the slicer to achieve a TRL 6 (space environment) level and to adapt the actual technique to SNAP, the other on the focal plane development of the detectors to validate the performances with the chosen technologies.

2.6.10.1 Slicer R&D

The proposed image slicer is of the same type as the one studied in the context of the NGST near-IR spectrograph (Allington-Smith et al., 1999; Le Fèvre et al., 1999). This technology has been ranked at NASA readiness level 5 by a panel of NASA experts in the context of the concept appraisal of pre-phase A NGST studies. The readiness level 6 is required to be "space qualified." Prototyping activities are on-going at Laboratoire d'Astrophysique de Marseille (LAM) and in collaboration with other European institutes to validate this technology both for large ground-based telescopes and for space applications, under funding by various agencies including ESA, CNRS and CNES. The R&D effort necessary to adapt this concept to the SNAP requirements therefore meshes nicely with on-going activities and will be in time with the R&D phase.

Specifically, we have an on-going program to qualify image slicers for space instrumentation. We are now in the process of developing a realistic prototype for a space-qualified unit, based on Zerodur-glass slices. By the end of 2003 we anticipate that the image slicer technology will be ranked at TRL 6. We are currently integrating the prototype and will conduct a set of tests for its qualification. Visible test at room temperature will permit us to completely understand the optical behavior of this technology. Afterward a 30 K test will be run in order to check the performance at cryogenic temperature. A vibration test with Ariane 5 specifications will prove the survival of launch. All principal technologies are identical for SNAP, except for a few parameters such as temperature. Some prototype work will be done during the two next years for complete validation for the SNAP case. Figure 35 shows the prototype integrated and ready for the test run.

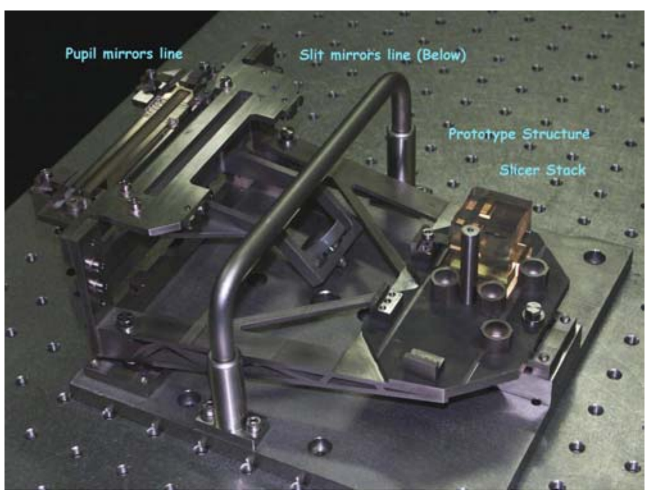

Figure 35. Slicer prototype integrated

2.6.10.2 Detector R&D

As the impact of various sources of noise is critical for the good performance of the spectrograph, a large fraction of the efforts in 2004 will be dedicated to the electronic noise minimization. A dedicated R&D program in France, supported by IN2P3/CNRS, will allow us to develop an expertise in electronics for IR detectors (E. Barrelet/G. Smadja et al.) and are charged to define the CCD technology and the optimal design for the spectrograph. Afterward, the chosen solution will be tested and characterized for the end of the R&D phase. Output documents will be a development plan for phase B/C/D. Planned developments include a first study of detector and electronics:

- For the detector, test benches are under development and have been ordered for optical and IR. An H1RG Rockwell detector has been ordered and is expected to be delivered January 2004. A dewar (80K-140K) will be fabricated which includes accurate temperature monitoring and monitoring photodiode allowing to test the Rockwell detector in the desired temperature range (leakage currents, readout noise, homogeneity, intrapixel variations, clock frequency, optimisation of multi-read scheme). Particular attention will be given to understanding the 1/f noise. Concerning the CCD evaluation, the radiation tolerance of small spectrographic devices will be considered. A Deep Depleted EEV CCD will be evaluated, including fringing tests.

- Actual activities on the electronic development are reported elsewhere and concern ASIC development in collaboration with the LBNL group with a contribution to a rad-hard CCD front end and the development of an ASIC modelled on the MEGACAM front end architecture. The MEGACAM-like ASIC for CCD readout will be tested and a readout demonstrator (FPGA + microprocessor) will be constructed.

2.7 Data Acquisition and Control

SNAP generates prodigious amounts of data and determining how to handle it in the satellite is an important activity during the R&D phase. Data generation time profiles, different processing options, telemetry rates, and ground station visibility hours all need to be modeled to arrive at an optimal conceptual design. An important R&D task is to document all the control and command functions required by the instruments and their interface to the on-board data management system. This research will generate critical input into the satellite design: weight, power, and volume of processors and memories; required telemetry bandwidth; and the number and availability of ground stations required.

The R&D tasks described below are

- Concept development.
- Implementation research.
- Requirements development.
- CDR planning.

The readout electronics transmits data for 30 seconds approximately every 300 seconds during photometric observations, outputting a total of 12 Gbits/image, uncompressed. The data are stored and over three Tb are transmitted every three days using a 300 Mbs downlink for approximately three hours. Collecting, processing, and making this data available to the telemetry system are challenging. As part of the challenge, we need to consider such items as redundancy, non-propagating failure modes, power, and packaging.

The SNAP instruments will have both common and unique needs to operate them. Under the research part of this activity, we will document the configuration and operational requirements of the instruments. These will eventually map into the low level command set to be executed under the direction of the observation program script periodically uploaded from the ground.

Conventional CCD controllers are quite bulky and, more important, power hungry. In a later section we describe development work on application specific integrated circuits for analog signal processing and digitization. This is motivated by reduced power and volume, higher integration and reliability, and radiation hardiness.

2.7.1 Progress in the past year

In the last year we have developed the block diagram for the instrument electronics, Figure 36. All imaging sensors on the focal plane with their readout electronics are on the left hand side. The central part of the block diagram shows the Observation Control Unit (OCU) and mass memory. The right side of the block diagram shows the power, telemetry and ACS systems. The current concept of the focal plane is that it operates at 140K and that all the detector control and readout electronics is located on the focal plane. The progress of module "CRIC ASIC" is described elsewhere. The block diagram shows redundancy implemented for the OCU, thermal control, focal plane control, power subsystem telemetry and ACS system. The redundancy for the control and readout of the spectrograph is implemented by dual set of detectors with corresponding control and readout electronics. The imager and star-guider sensors only have redundant connections to the OCU, but do not have redundant detectors.

2.7.2 Concept development

In this set of activities we identify the internal needs of the data management system and the impacts of external requirements and limitations, and establish the criteria for selecting between alternative implementations.

2.7.2.1 Focal plane electronics

The focal plane has two kinds of sensor modules, CCD for visible light and HgCdTe for NIR. In Figure 37 and Figure 38 we show the CCD and HgCdTe control and readout electronics. Operating these modules at 140K will required detail analysis and tests of chosen components. The final choice, if commercially available components don't meet the requirements, will be to implement this function in one or two custom circuits.

2.7.2.2 Model data volume and rate

SNAP can generate 12 Gbits of exposure data in 30 seconds every 300 seconds when it is operating in optical photometry mode. This instantaneous data rate must be memory buffered to match any reasonable telemetry bandwidth. Lossless compression can be applied to the data before storage or algorithmic processing of multiple images can be performed to reduce the size of memory buffer required.

2.7.2.3 Study memory/CPU/telemetry impacts

SNAP images are formed by adding four or more exposures. The exposures are cross-correlated to remove contamination by cosmic rays. There are two approaches on where to combine the exposures into cosmic-cleansed images, on the spacecraft or on the ground. Co-adding exposures on the ground would require very little satellite CPU resources and software, assuming data compression is done in hardware. But large memories and high telemetry rates are certainly required. Co-adding images in the satellite can reduce the telemetry rate requirements by a factor of four but requires sophisticated on-board software operating in several CPUs. For example, calibration codes would have to be executed in space since up-link rates are likely limited to a few tens of kilobits per second and transferring multi-Gbyte files is impractical. Another restriction is that only one cosmic ray cleanup algorithm can be used and this must be perfectly tuned prior to launch. Such code would also be complicated by the need to dither image placement on the imager for each exposure.

We currently favor transmission of all exposures without processing other than compression. We also believe that without complex on-board processing it will be easier to design the electronics and software.

2.7.2.4 Develop data processing concepts

Here we need to compare the different data processing paths that we might execute in the satellite and understand their impact on the above. The metric to be used includes memory size, number of CPUs, quantity of software, telemetry rate, doing no harm to the data, inter alia.

2.7.2.5 Document SNAP instrument control

On the ground, an observation command set will be assembled to direct the instruments' autonomous activity for a period of time, say three days. The details of what needs to be accommodated in this command set needs to be negotiated with the ground station concept team. Since the instruments will be developed in parallel at more than one site, weight should be given to a concept that allows multiple, local development efforts that are easily integrated into an instrument package very late in the construction phase.

To execute an observation program, the instruments are cycled through various modes of operation, for example, electronics configuration, sequencing shutters and filters, reading out detectors, flashing calibration lamps, erasing persistent images, and more. There will be health and environmental monitors in the instruments to insure data quality. Under this task we need to document instrument control and monitor needs. An early determination of these needs can allow us time to develop a common physical and logical interface to both the data collection system and the control system for all the instruments.

The information transferred across the interface between the instruments and the spacecraft control and telemetry system needs to be defined. Clearly the observation command set must pass from the telemetry system to the spacecraft control and then to the instrument control unit. If an instrument control CPU is executing the observation commands, it needs to communicate back to the spacecraft control with information such as the desired pointing direction. An area requiring special attention is the how the fine star guider data are handled to select stars and provide high rate updates to the satellite attitude control system.

2.7.3 Implementation research

In this set of activities we explore potential physical implementation of the data management system that match with a still fluid set of requirements.

2.7.3.1 Survey available hardware/interfaces

It is undesirable to develop a new untried data acquisition system for SNAP unless absolutely required. A survey of existing space memory, CPUs, and architectures needs to be performed, including consultation with spacecraft vendors and memory system vendors.

For instrument control and monitoring, we will look for existing protocols and physical implementations and study their suitability for SNAP.

2.7.3.2 Survey of existing/proposed systems

SNAP is not alone in learning how to deal with large satellite data sets. We will spend time to research what has been done in other satellites and what is being considered for the future. There is a wealth of information being generated by the NGST on this issue.

For compression studies, a variety of algorithms are available. One that is much discussed for space imaging is the Rice algorithm; it is available in both software and hardware forms. For space images, compression efficiency is often determined by read noise. We can use dark images from our CCD test stand to measure how well they compress. Access to 16-bit unprocessed Hubble images will also be useful.

2.7.4 Requirements Development

At the end of the R&D phase we will have made the decision on the extent of on-board data processing we require based on tradeoffs of CPU versus memory versus telemetry. Implicit in this is the choice of a data compression scheme.

A requirements document capturing all the interfaces to instrument data and control, spacecraft control and telemetry, and ground station instrument control messages will be generated. A block diagram of the architecture will be developed showing these interdependencies and data rates.

2.7.5 CDR planning

The deliverable at the end of R&D is a cost and schedule for the engineering and construction of the on-board data management electronics. This will be supported with a requirements document and block conceptual design.

2.7.6 Planning for long lead procurements

At this time, no long lead procurements are anticipated.

2.7.7 Risk assessment

One of the purposes of this research is to minimize the probability that custom solutions will need to be designed and qualified during the construction phase. Our architecture will be strongly influenced by available commercial or other space-proven hardware.

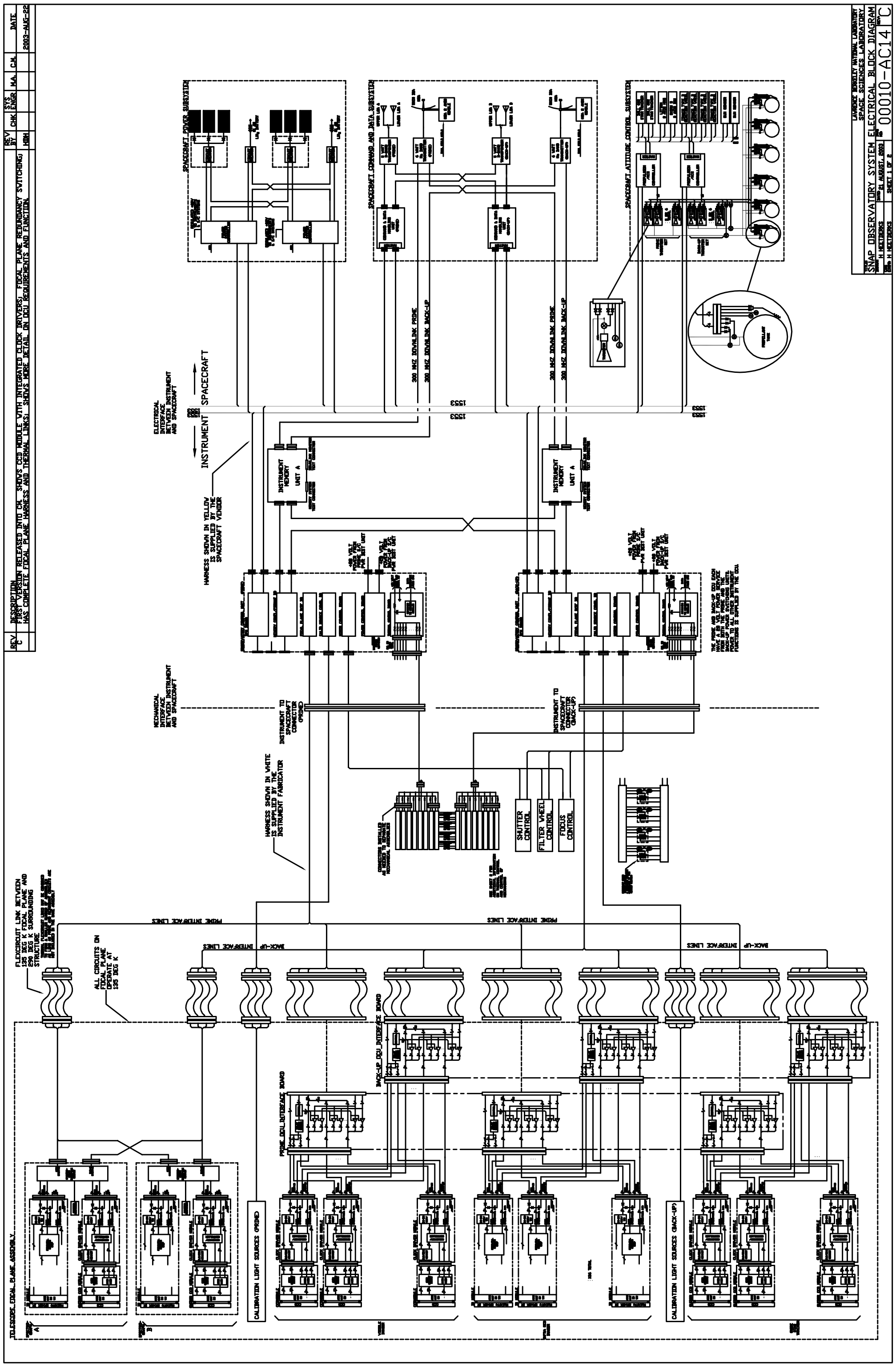

Figure 36. Block diagram of the instrument electronics.

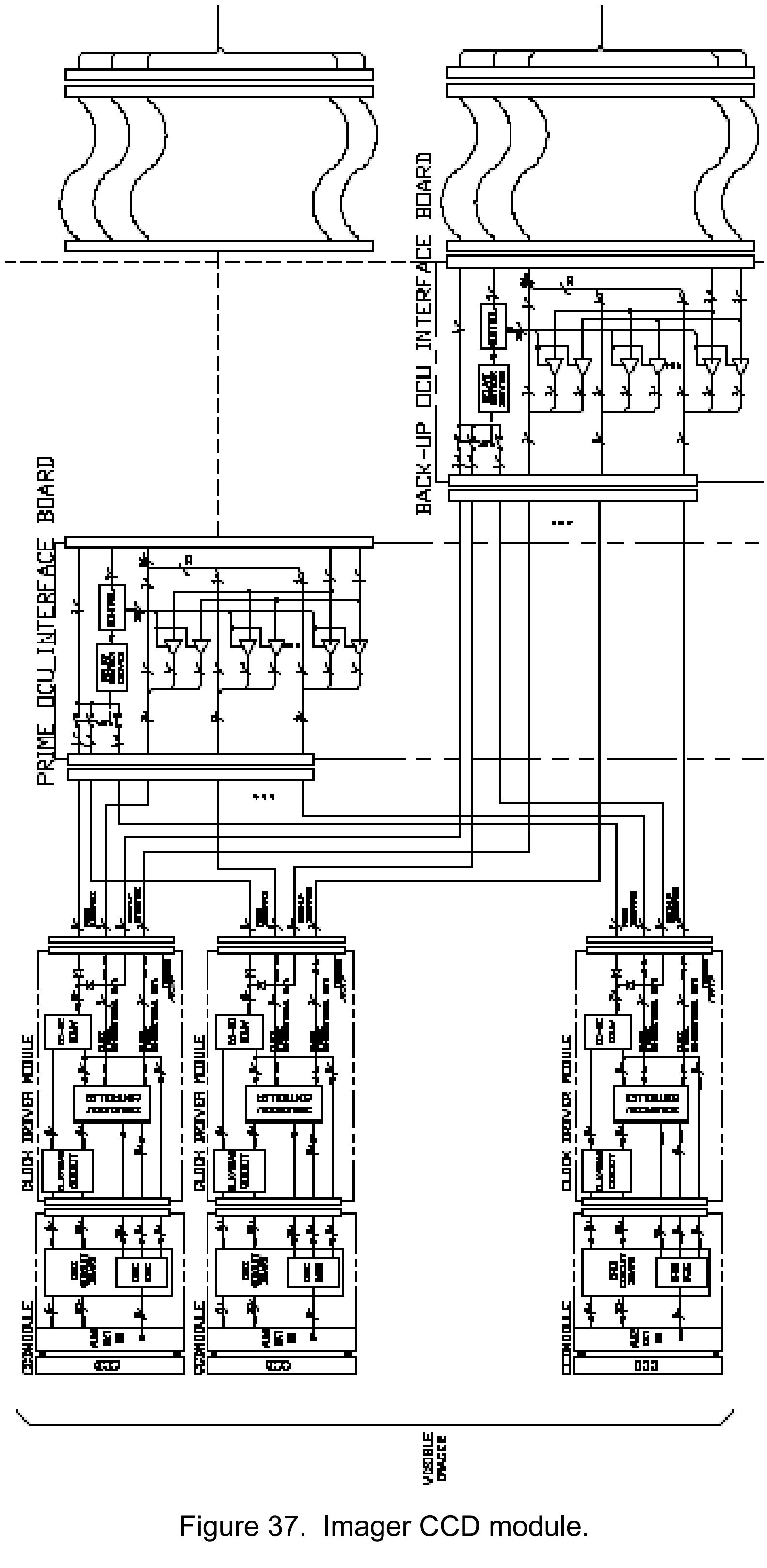

Figure 37. Imager CCD module.

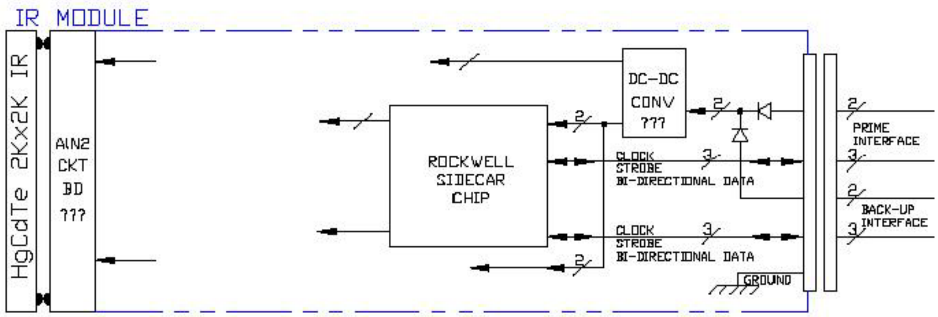

Figure 38. MCT focal plane module.

2.8 Front-end Electronics

The SNAP instrument electronics will perform analog signal processing, digitization, clock, control, bias generation, monitoring, and data acquisition for the wide-field camera, spectrograph and star-guiders. A concept for the electronics chain has been developed to read out the SNAP CCD and the HgCdTe sensors.

The block diagram of the readout electronics for the CCD is shown in Figure 39. The major blocks per CCD sensor are:

1. DC voltage generation
2. Clock generation
3. Correlated double sampler and analog to digital converter (CRIC ASIC)
4. Temperature monitoring
5. Interface to instrument configuration bus
6. Interface to image data buffer

The block diagram of the readout electronics for the HgCdTe is shown in Figure 40. The major blocks are:

1. DC voltage generation
2. Clock and bias generation in the Rockwell SIDECAR ASIC

Due to the large number of sensors and the limited power, weight and volume that can be accommodated by the spacecraft, the conceptual design has evolved towards miniaturization of the front-end electronics by means of application-specific integrated circuits (ASICs). While the requirements for the front-end circuits are within the realm of similar custom ICs that have been designed for high-energy physics experiments, any ASIC development effort that combines analog and digital processing invokes some schedule and technical risk. The electronics R&D program emphasizes an early effort on front-end ASICs in order to mitigate these. At the end of development, the parts will be brought together to build a proof-of-principle front-end system to read out both HgCdTe and CCD sensors.

The remaining electronics needed for the bias, control and clock generation, power regulation and data compression are likely to be based on commercially available parts or simple VHDL digital circuits that involve much less risk. R&D in this area described in the DAQ section will focus mainly on the requirements and conceptual design. Power consumption, thermal requirements, and physical volume are needed inputs for the spacecraft design, and will be described in an interface control document.

The SNAP instrument front-end electronics must address several challenges, including very low noise, large dynamic range, low power consumption and radiation tolerance. In addition it must be robust and reliable enough for operation in space. Conventional implementations relying solely on discrete parts have been surveyed and will exceed any reasonable satellite power budget. For CCDs, commercially available integrated circuits have also been considered; there are none currently available that meet SNAP requirements. For their NIR sensors, Rockwell is developing an ASIC (SIDECAR) that may meet SNAP requirements for HgCdTe readout. For the CCD readout we have developed a custom integrated circuit, the CRIC chip. With minor modifications it can meet the requirements for HgCdTe readout as well and functions as a backup in case the Rockwell IC does not meet our requirements or schedule. Both the LBNL and French groups in SNAP have extensive experience with custom integrated circuit (IC) design, including the design of radiation-tolerant circuits in commercially available deep submicron CMOS. Operation of the readout electronics at cold temperatures enables locating it very close to the cold focal plane, eliminating long cable runs for small analog signals, reducing the cable plant and reducing the complexity of the overall thermal, mechanical, and electrical design

2.8.1 Detector signal characteristics

The SNAP satellite instrumentation suite will use science grade silicon CCDs and HgCdTe sensors. An important difference between traditional CCD devices and the near-infrared sensitive HgCdTe sensors is that HgCdTe can be non-destructively read out and multiple samples can be used to reduce the read noise.

CCDs require several clocks to move the pixel charge for readout. A set of clocks performs a parallel shift of pixel columns into a serial shift register. The voltage swings of the clocks are approximately 10 V, the parallel clock capacitances are ~20 nF, and the serial clock capacitances are ~10 pF. The drain voltages for the output FETs are 20–25 V and the depletion voltage is 30–100 V. Removal of reset noise can be performed pixel-by-pixel with an analog correlated double sampler technique.

For HgCdTe devices, the reset and signal sample times are temporally disjoint and the correlated double sample operation is performed digitally. The pixels can be non-destructively read. For example, the pixels are reset, the reset levels are digitized and stored, and after an exposure period the pixels are digitized again. A digital subtraction of the two arrays accomplishes the CDS function. Other noise reduction techniques, multiple Fowler sampling and up-the-ramp sampling are also possible in the digital domain. Multiple Fowler sampling does many consecutive reads after reset and after exposure to statistically reduce the read noise. Up-the-ramp sampling makes periodic, continuous reads of the pixels during the exposure. This also reduces the impact of read noise and can detect cosmic ray charge deposition. The readout clocks for these devices are CMOS logic levels and the maximum output signal is 500 mV.

2.8.2 Finalize requirements

The requirements document for the SNAP instrument electronics must consider both CCDs and HgCdTe sensors and their use in both the wide-field imager and the spectrograph. While there will be some small differences in requirements among these use cases, the overall goal to maintain compatibility with all sensor types in SNAP is a primary requirement for the electronics. Our work so far indicates that a modest flexibility is achievable to provide this compatibility with a small extra effort. The requirements document for the SNAP instrument electronics will discuss requirements for both CCD and HgCdTe operation, including:

- On-detector electronics.
- Analog signal processing.
- DC voltages and their cycling.
- Clock parameters such as levels and shapes.
- Clock sequencer and modes of operation.
- ADC interface.
- Data processor/memory interface.
- Local resource configuration and control.
- Overall power and control.

Once assembled, the draft requirements document must be formally reviewed and finalized.

2.8.3 Development of conceptual design

After agreement to the requirements document, the system architecture will be developed and detailed in a block diagram. A good deal of engineering time will be spent on this high level design to make trades between ASIC and conventional parts implementations. The use of ASICs is motivated by at least three important concerns: 1) power consumption, 2) size and weight of the whole system, and 3) reliability. Experience in high energy physics has shown that the use of ASICs for readout of a large number of detector channels can reduce the size of the front-end electronics and the needed power. Large standing currents to load and unload highly capacitive interconnect media such as copper tracks or wire bonds on hybrids or printed circuit boards can be reduced and power saved. As an order of magnitude, the stray capacitance to ground of an interconnect between two chips a distance one centimeter apart on a multi-layer PCB is of the order of 1 pF. This is to be compared to 10 fF for a one-millimeter interconnect on an ASIC.

To date for CCD readout, we have developed and tested an ASIC that implements a dual-slope correlated double sampler. This is a 12-bit resolution, 16-bit dynamic range circuit implemented with three auto-switching gain ranges.[6] A second iteration of the CDS chip is planned for submission early 2004. This iteration will include an integrated pipeline ADC.

The CCD controller is another candidate for ASIC implementation, though commercial solutions or FPGAs may also provide a solution. The generation of clock waveforms and control voltages for the CCD and HgCdTe sensors requires high voltage, limiting the choices in integrated circuit technology and posing more risk. We will consider both discrete and ASIC solutions for this aspect.

---

[6] J.-P. Walder et al., “A Low Power, Wide Dynamic Range Multi-Gain Signal Processor for the SNAP CCD,” submitted to IEEE Trans. Nucl. Sci.

Rockwell is developing an ASIC for HgCdTe readout for NASA. We are in contact with Rockwell and will follow this development effort closely and are scheduled to receive prototypes for detailed characterization. This work would be done by Cal Tech. If the Rockwell ASIC does not meet SNAP requirements, it is also possible that we could contract with Rockwell to submit a modified version that would be suitable for SNAP. They have provided us with an estimate for this type of work and we carry this as a contingency.

In the process of developing a conceptual design it is important to maintain fallback options that can be exercised in the event that R&D does not succeed in meeting the target goals. We have a number of fallback options for the SNAP electronics. For example, if we fail to demonstrate successful cold operation of the control electronics, the fallback option is to remove it to the warm area. Similarly if the power consumption of the control electronics cannot be reduced to a level consistent with the thermal constraints on the focal plane, we will either remove some functionality to the warm area, or explore more sophisticated cooling techniques that can handle increased power. It is also important to have a fallback in case the Rockwell ASIC for the HgCdTe readout is unsuccessful or fails to meet our requirements. In the former case we would adapt our CCD ASIC development for readout of the HgCdTe sensors; in the latter case it we would negotiate with Rockwell to see if they could develop a SNAP-specific ASIC that did meet all of our requirements.

2.8.4 Design prototype system

To be able to test the ASICs several parts of the readout system that will probably use conventional technologies need to be designed and built. For example, front-end test modules are being built to test CCDs and CRIC chip together operating at 140K.

The completion dates we have scheduled for the fabrication of ASICs follow from submission dates for multi-project prototyping services. A first iteration of the CDS ASIC was submitted in January 2003. Printed circuit boards and computer interfacing and test software have been developed. Stand-alone testing is completed in 2003 has showed that the CRIC chip meets the performance requirements for SNAP. The second iteration of the CDS test chip, incorporating an ADC, is scheduled to be tested and available for system tests summer 2004.

A goal of the R&D period for HgCdTe readout is to demonstrate a complete readout chain from the sensor to the digitization of the data that meets all of SNAP's requirements, whether it is based on the Rockwell ASIC or our own CRIC chip. This includes testing at low temperature and irradiation.

2.8.5 CDR planning

A major deliverable at the end of R&D is a cost and schedule for the construction of the front-end electronics. The development of a comprehensive requirements document early in the process will help insure that all the necessary items are identified. The program of ASIC development and conventional parts selection will establish the production costs for these items. We note that ASIC development may not be entirely complete on the time scale of CDR but this does not preclude costing production parts on the basis of one or two prototype runs. The cost and schedule for construction will be developed during the last six months of R&D using as input the actual material costs and labor efforts required during prototyping of the components described above.

2.8.6 Planning for long lead procurements

It is likely that at the time of CDR we would seek approval to move ahead with the procurement of the ASICs as fast as possible, subject to the state of the prototype development. There are several reasons for this. One, ASIC fabrication runs have an associated risk of failure where months of delay can be incurred while parts are re-fabricated. Two, a chosen semiconductor technology may not have a long lifetime and therefore may no longer be available if there is a large gap between development and production. Three, an engineering team will have been assembled during the design and prototyping stage and continuity of personnel and familiarity can be lost and additional engineering costs incurred if parts are not ordered and tested in a timely manner.

2.8.7 Risk assessment

There are risks associated with developing custom ICs. Design iterations may be required. Fabrications may fail or be delayed. But the potential costs are time delays. Success can eventually be achieved. ASIC development for SNAP is actually itself a risk mitigation. We are also trying to dramatically reduce the number of parts that need to be tested for space environment by using ASICs.

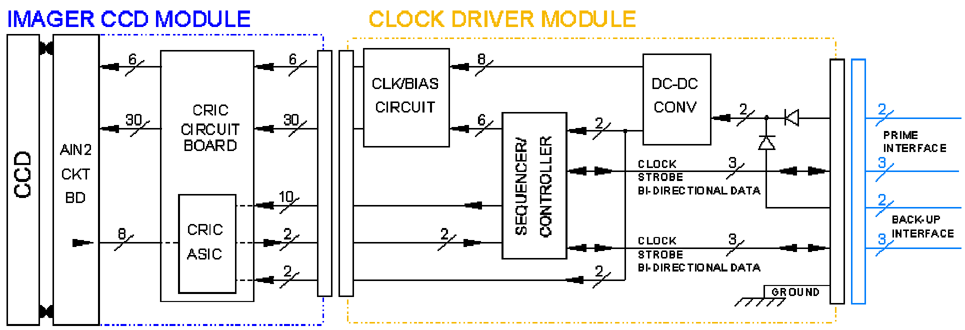

Figure 39. CCD front end readout module.

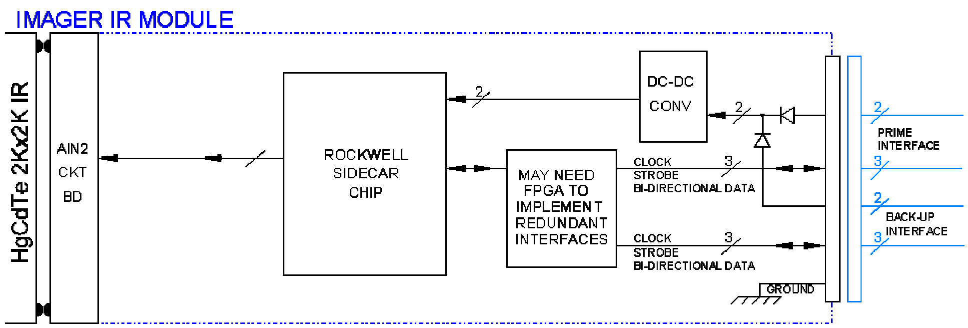

Figure 40. NIR front end readout module.

2.9 Mechanical systems

In this section we briefly describe the mechanical components and the activities surrounding them during the R&D phase. The needed R&D effort is considered modest. Mainly, the promising design concepts and interfaces with the telescope and spacecraft will be developed. This is reflected by the planned cooperative nature of the engineering efforts, between the satellite systems engineering team and the instrument group.

2.9.1 Shutter

SNAP will have a mechanical shutter located behind the telescope folding mirror. A concept is show in Figure 41. The shutter serves multiple functions: normal exposures with precise timing, fast exposures for calibration on bright objects, and a flat for calibration illumination. The R&D tasks are mainly the conceptual development, and follow on identification of available solutions, which is needed for costing and scheduling. Redundant and fault tolerant designs plus low noise operation are a focus.

During the R&D phase, the shutter concept team will interact with the calibration team to understand the minimum exposure times desired and practically achievable. Joint activities with the System Engineering group will be budgeting space and mass, plus insuring that any net momentum disturbance during shutter motion can largely be negated, or be accommodated by the attitude control system,

2.9.2 Shield

Following the shutter, the optical beam expands to the focal plane inside a housing we will simply refer to as the shield. This shield must accomplish several things:

- Isolate the cold focal plane from the warm satellites thermal radiation.
- Block stray light from impinging on the focal plane.
- Attenuate the cosmic ray flux as much as is practical.
- Absorb backscattered light from the surface of the sensors and their mounts.

The role of the shield as a cosmic ray attenuator makes this object potentially quite massive. Its placement and stability are not critical, when compared to the focal plane. A simpler attachment scheme, albeit still with thermal isolation, can be used. To refine the mass estimate, the R&D plan includes simulations of the charged particle attenuation using standard computer transport codes. The environment is the measured fluencies of solar and galactic particles. A subtlety is that CCD images, in particular, are polluted more by the shear number of charged particles rather than the charge or energy of any one particle. A balance between attenuation of the primary incoming flux and their resulting secondary cascades needs to be considered in this shielding study.

2.9.3 Cold plate

A robust annular molybdenum plate is the primary precision mount for the imager sensors, CCDs and HgCdTe, and the spectrograph (Figure 43). The plate is maintained at 140 K by connections to a large passive radiator. Small heaters will provide the desired temperature regulation. The plate is supported by kinematic mounts to the telescope support structure (Figure 44). The focal plane will not have mechanical adjusters and must be stable to a couple of tens of microns in focal depth. These mounts are envisioned to also provide the thermal isolation between the warm telescope structure and the cold plate. A concept for the mounts is shown in Figure 45 that is cluster of metal balls in point contact to provide the desired thermal isolation. An R&D activity is to design, build, and test a larger unit that is adequate for the SNAP focal plane. These designs will be a joint effort on concept development among the instrument mechanical engineer and mechanical and thermal engineers in the System Engineering group.

2.9.4 Cooling

The cooling source for the 140 K focal plane cold plate and its sensors is an approximately three square meter plate that radiates to space. Figure 46 shows the radiator and its attachments to the instrument. If this radiator operates at 120 K, there will be 35 W of 140 K gross cooling available at the cold plate. There is no development required during the R&D phase for this device. The main effort will be interaction between the instrument and the system engineering teams to keep the electrical power dissipated by the sensors and their electronics plus other thermal loads and the parasitic losses within the cooling budget.

The thermal paths between the radiator and the cold plate are termed heat straps. There approximate position is shown in Figure 47. At the moment these are thought to be commercially available parts using thousands of high thermal conductivity carbon fiber strands. Such a unit is shown in Figure 48. The flexibility of these links decouples forces and motions of the radiator from the focal plane. No R&D effort is required for these items.

2.9.5 CDR planning

A major deliverable at the end of R&D is a cost and schedule for the construction of the mechanical components of the focal plane array.

2.9.6 Planning for long lead procurements

No long lead procurements are anticipated

2.9.7 Risk assessment

We do not identify any high risk issues associated with developing the mechanical components described above.

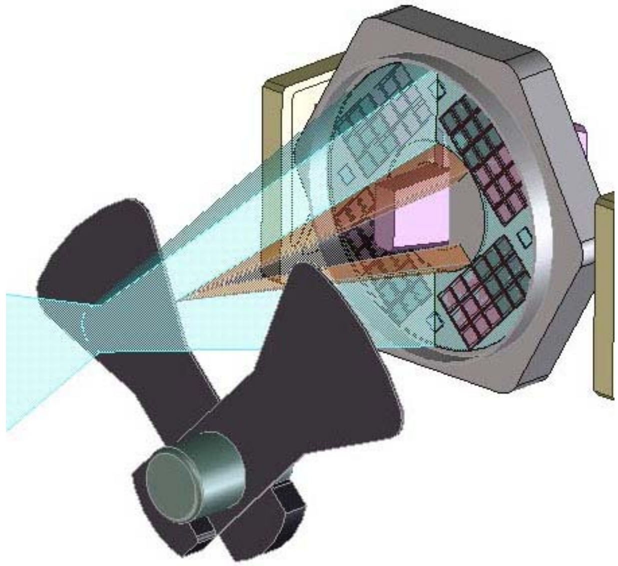

Figure 41. Shutter concept.

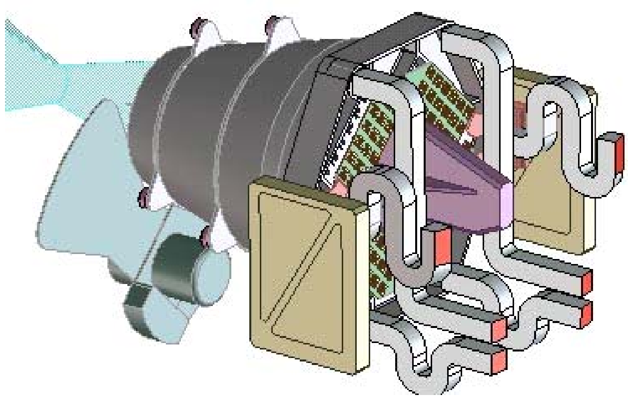

Figure 42. The shield is the conical shape between the shutter and the focal plane

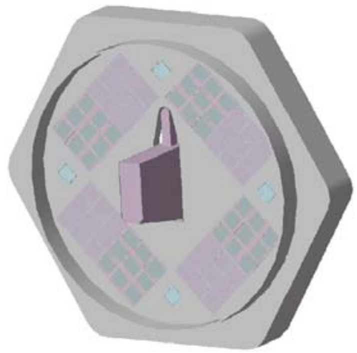

Figure 43. A front view of the cold plate showing CCD and HgCdTe sensors mounted

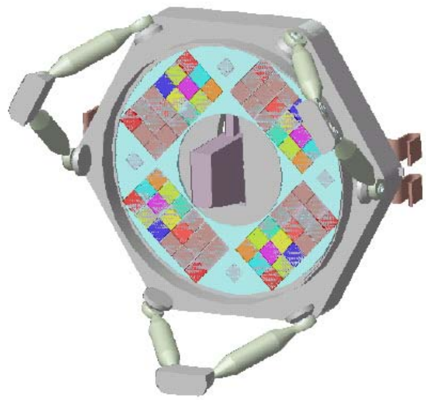

Figure 44. Concept of bi-pod mounts providing kinematic support of the cold plate from the telescope structure.

Figure 45. Candidate concept for the thermal-isolation mounts of the cold plate to the telescope.

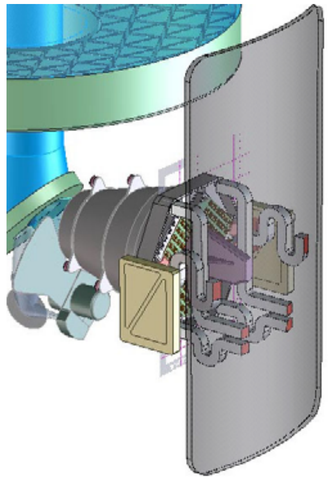

Figure 46. View of the space thermal radiator relative to the rest of the instrument.

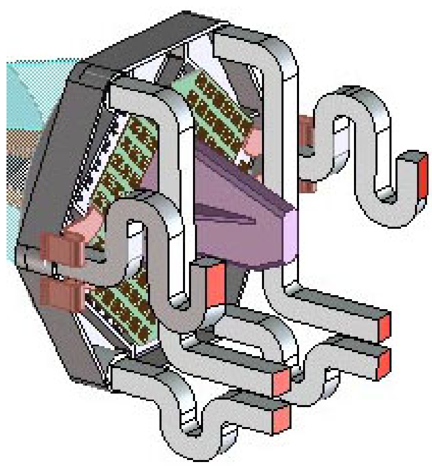

Figure 47. Thermal conducting S-links showing their attachment to the cold plate. The near ends of the links are attached to the radiator.

Figure 48. Example of commercially available S-links comprised of tens of thousands of flexible carbon fibers.

Section 3. Calibration R&D

The R&D tasks associated with SNAP Calibration are driven by the need to prepare a thorough specification of the spectrophotometric calibration (absolute color calibration), the data processing pipeline (calibration pipeline), the instrument calibration requirements, and the interfaces between the calibration team and the instrument and ground systems teams. This specification will in turn permit the development of a sound plan for achieving the required color calibration precision.

1. Our requirements will be written with careful consultation with scientists (astrophysicists, solar physicists, space scientists) having established credentials in the various aspects of calibration at research institutions and at the National Institute of Standards and Technology (NIST). Toward this end we will continue to form a calibration team whose cumulative experience is appropriate for a project of the scale of SNAP.

2. Absolute Color Calibration: Our requirements will be carefully prioritized with respect to potential tradeoffs that control the calibration error budget. We have identified several possible routes and we anticipate that as further constraints are better understood, our trade studies will allow us to properly assess the different methods and select the one best suited for the SNAP science.

3. Calibration Pipeline: Our specifications for a calibration database to deliver the required science will be refined. The pipeline produces the calibration products used to process each data image: a) dark and bias frames to remove dark current and pedestal effects; b) flat fields to control for the high-frequency, pixel to pixel variations in response; and c) photometric zero-point and spectrophotometric references to determine the flux and colors. These calibration products must be monitored during operation. During the R&D phase we will develop, in concert with the instrumentation groups, diagnostic metrics of system behaviors.

4. Instrument Calibration: By the end of the R&D phase we will have developed a detailed calibration plan tracing all steps in the calibration process for each instrument. Each step will include the procedures and the means to validate those procedures.

Since the methodology for each aspect of calibration is already established, we do not anticipate having to engage in basic prototyping. Both instrument calibration and calibration pipelines have been established by past and present, space missions, e.g., International Ultraviolet Explorer (IUE), Hubble Space Telescope (HST), Chandra X-ray Observatory, and the Space InfraRed Telescope Facility (SIRTF). However, the R&D phase provides the needed time span in which to conduct concept development and to refine our requirements for SNAP’s more demanding calibration component, the absolute color calibration.

3.1 Requirements Overview

The main result of our R&D study is a detailed plan for calibration which will be carefully reviewed by all members of the calibration working group prior to the scheduled CDR project milestones. Here we present a preliminary list of the requirements that will be specified during the R&D phase.

1. Instrument calibration:
   - In flight and ground methods
   - Performance vs environment
2. Absolute Color Calibration:
   - Minimum error budget
   - Minimum transfer errors from primary source to target object
   - Maximum allowed systematic errors in the optical
   - Maximum allowed systematic errors in the near infrared
3. Standard Star Network
   - Base source selection: sun, NIST blackbody
   - Fundamental and primary star selection: different brightness and spectral types
4. Calibration Pipeline:
   - Quality of flat-fields
   - Frequency of calibration observations
   - Diagnostics to monitor temporal changes
   - Diagnostics to monitor frequency shifts in response
   - Impact of calibration hardware (e.g., lamps, shutter) on instrument design

3.2 Calibration R&D Trade Studies

3.2.1 Instrument calibration

The basic concern of calibration is to understand the instrument response to incoming light as a function of wavelength, intensity, environment and time. Options for establishing ground calibration of the instruments are end-to-end (the entire telescope) and piece-wise. In concert with the instrument teams we will study how the science data can be used to measure and diagnose changes in in-flight performance. For example, the SNAP primary science mission will observe the same fields every four days through each filter, and thus, each of the thousands of stars in each field. This data time series may be used to monitor changes in response.

3.2.2 Calibration pipeline

A software pipeline produces the calibration products used to process each data image: dark and bias frames to remove dark current and pedestal effects, flat fields used to divide out the high-frequency, pixel to pixel variations in response, “super flats” to divide out the low-frequency variations across each detector. Wavelength solutions determined from lamp emission spectra are applied to spectral data. The final stage is the application of the zero-point and spectrophotometric references. It is well known that accurate flat fields are important for obtaining well calibrated data. Broad spectrum lamps are typically used, though uniformly illuminating a large field of view over both the optical and near infrared can impact the number and spectral range of the lamps, their location within the optical bench, shutter precision and possible diffusing surface. Alternatives to relying solely on lamps for the flat fields are to use zodiacal light, moonlight, earthshine, and/or median filtering deep sky images.

3.2.3 Absolute color calibration

A number of trade studies have been identified. Achieving high precision in the color calibration demands precise control of systematic errors throughout the spectrophotometric calibration chain. The overall calibration of the SNAP optical and near infrared imagers and the spectrograph will be conducted through several routes. We envision employing a variety of well-studied stars, including the sun, and also performing indirect transfer calibrations that permit comparison with NIST irradiance standards to close the loop with fundamental MKS quantities. We expect that other trade studies may become necessary as our design space is explored in further detail. Here we list the known major trade alternatives along with brief explanations of their system impacts:

3.2.4 Artificial point sources

Precise blackbodies for irradiance measurements have been used for over thirty years to calibrate optical systems on the ground and in space. These integrating spheres are calibrated by NIST. The sun itself can also be used as an irradiance standard. Precise calibration of the sun is currently under way with SORCE, a space-based experiment. Since our target objects are much fainter than these standards, we need to determine an optimal attenuation method suitable for the mission.

3.2.5 Standard star network trade studies

Absolute spectrophotometric calibration in the optical has been carried out on the ground for several stars, most notably Vega. HST spectrophotometric calibrations are based on models of four pure hydrogen white dwarfs from the UV to the IR and one solar analog in the IR, fixed on Landolt V band photometry.

The Sloan Digital Sky Survey (SDSS) developed its own calibration program based on three primary standard stars whose absolute spectrophotometry traces back to the absolute calibration of Vega. The SDSS network of secondary standards was developed with three telescopes of aperture 0.5 m, 1.0 m and 2.5 m (the Sloan telescope itself) in order to span the required dynamic range in brightness from the bright primary standards to the faintest secondaries in the optical. The achieved precision ranges between 1.5% v′, g′, and r′ and 3% u′ and i′.

SNAP is a space observatory, requiring a similar network of standard stars for the SNAP filters but with a longer wavelength reach – from 350 nm to 1700 nm. Several choices are available for establishing SNAP's own network. The first is to carry out a program from the ground. However, the atmosphere's many absorption bands in the near infrared may vitiate the reliability of the planned NIR bandpasses. The second option is a space program, using the Hubble Space Telescope and perhaps also SNAP itself (after launch), which bypasses atmospheric effects. Other options include a mix of ground, space and balloon platforms. The total cost and schedule of the calibration program depend on the choice of platform(s).

3.2.6 Selection of standard stars

Bright fundamental standard stars must be chosen and calibrated against NIST traceable irradiance standards. The sun, for our purposes, is considered as an MKS irradiance standard. We have selected our fundamental flux standards to be the HST calibration set of white dwarf and GV (solar analog) stars, as well as Vega. Primary standard stars are calibrated spectrophotometrically and photometrically with reference to these fundamental standards, and must be selected such that a few lie in the SNAP fields. Primary standard stars will include not only white dwarf and solar analogs, but also stars covering a range of spectral types, suitable for use by both the optical and the near infrared detectors. Spectrophotometric, or color calibration, secondary standard stars covering a range of spectral types and brightness in and near the SNAP fields need to be identified and monitored to exclude variable objects. The secondary standards are calibrated photometrically against the primaries.

3.2.7 Error budget

Other trade studies going hand in hand with the above concern the number of steps needed to transfer the primary calibration to the target objects, the identification of systematic errors, and the consequent carry over of systematic effects to each step. This will affect the achievable precision. We note that this depends on the platform(s) chosen as do the relative contributions of each systematic.

The goal of these studies is a calibration error budget, in which the magnitude and distribution of the various sources of error are correctly identified. Maintaining an overall requirement that meets the needs of the science program may require some flexibility on the individual items. This error budget will be sent for review by experienced astrophysicists.

Section 4. Ground Segment R&D

4.1 Segment Definition

The SNAP Ground Segment consists of all ground systems required to communicate with the spacecraft to send command and control data, receive scientific and engineering data, and process all data in a timely fashion as required to operate the spacecraft and carry out the SNAP scientific mission. To accomplish these tasks, the Ground Segment is divided into Mission Operations and Science Operations.

Mission Operations will:

- Receive science observation requests from Science Operations and translate these into Command and Control sequences to be transmitted to the spacecraft.
- Up-link Command and Control data to the spacecraft.
- Track the spacecraft and determine ground station availability.
- Monitor spacecraft environmental and engineering parameters to ensure proper operation.
- Receive and buffer scientific and engineering data during down-link at orbit perigee.
- Transmit the data to Science Operations for processing and analysis.

Science Operations will:

- Receive down-linked data from Mission Operations.
- Verify data validity and reformat for science processing.
- Apply all current calibrations as required for converting raw images into science-quality images.
- Analyze the images to identify supernovae and other astronomical objects of interest.
- Update the scheduler to communicate additional observation requests to Mission Ops.
- Catalogue and archive the astronomical objects for further analysis.
- Provide computing and software resources for simulation studies to optimize the mission plan and instrument design.
- Provide computing and software resources for supporting calibration functions.

4.2 Mission Operations R&D Issues

The Berkeley Ground Station (BGS) located at UCB Space Sciences Laboratory currently hosts Mission Operations for the High Energy Solar Spectrographic Imager (HESSI) mission. In support of this and other missions, the Berkeley Ground Station has built up much of the infrastructure and expertise necessary for carrying out the SNAP mission. Thus for most of the Mission Ops functions for SNAP, there are no R&D issues. The few exceptions are:

- Upgrade of the antenna dish for Ka- band telemetry.
- The current BGS antenna is an 11 meter diameter dish used for S-band telemetry. To work for Ka-band, the dish surface would have to be re-worked to sub-millimeter tolerance. This will be investigated but it is likely that a new dish will be required.
- High speed data buffer and link to Science Ops at LBNL.
- The data rates for SNAP are higher and will require a new buffer and link. This will be specified during the R&D phase.
- Contingency Plan for back-up ground station(s) when BGS is down.
- Several alternate stations with Ka-band capability are possible options so a cost/availability trade study will be undertaken in the R&D phase. Data storage and delivery to LBNL will have to be understood and specified.

4.3 Science Operations R&D Issues

4.3.1 Software architectural and framework issues

The high-level workflow management functions of Pipeline Manager for processing data, Scheduler for managing the observation request queue, and Exception Handler for dealing with failures must work together in a "closed loop" manner, a challenging architectural design. In addition, the framework that defines the overall software environment must be in place before developers can begin to write consistent code.

The Simulation Architecture is nearly complete. As the simulation implementation begins, the architecture design will move on to the Science Ops code.

4.3.2 Software product trade studies

The basic data processing steps are similar for many space-based and even some high-volume ground-based projects. Many software products and packages have been developed for performing these basic functions. Much of the Science Ops R&D effort will be devoted to evaluating these products for direct use or adaptation in SNAP. Re-use of debugged, battle-tested code is extremely cost effective where applicable. To this end, we have initiated a joint study with a team from the Space Telescope Science Institute (STScI) who developed data processing packages for the Hubble Space Telescope (HST). We are particularly interested in the following products:

1. OPUS, the HST Pipeline Manager
   This package is the "backbone" that manages the various modules that carry out the pipeline analysis functions. OPUS can manage several simultaneous pipelines and contains a graphical monitor of progress and problems.
2. SPIKE, the HST Scheduler
   This product assembles observation requests from approved science programs, examines the various constraints on observation requirements and spacecraft operational requirements, and applies an optimization algorithm to determine the "best" observational sequence.

3. DADS, the HST Data archiving and distribution product
   This product uses a catalogue archive to make data available to scientific queries. In includes “on-the-fly” recalibration capability.

This study has now been completed and the report documents the trade studies, operations concepts, ground system architecture and estimated development costs.

The SNAP team is also working with the Supernova Factory (SNFactory) group to test some of the software products in a “real world” environment that has many similarities to the SNAP mission. The SNFactory uses the Near Earth Asteroid Telescopes to search for nearby supernovae. When the analysis pipeline identifies a candidate, a scheduler is used to queue spectroscopic follow-up on a University of Hawaii telescope at Mauna Kea. As part of the SNAP R&D program, we have ported OPUS to LBNL and started to evaluate its applicability as the SNFactory pipeline manager. In addition, we are helping the SNFactory team identify a scheduling package. We expect that this symbiosis will facilitate migration of SNFactory experience and even testbed code into SNAP and we consider it an important element of the R&D program.

4.4 Simulation R&D Plan

Simulation is the link between the SNAP science goals on the one side and the instrument requirements and mission operational profile on the other. In the past, many of these requirements and optimization studies have come from analytical techniques such as the Fisher Matrix formalism for error propagation. Specific questions were answered by very focused studies and calculations. While this has served us well, some of the issues are so complex and inter-dependent that a full Monte Carlo simulation of the astrophysical and instrumental effects is required. We now have an end-to-end Monte Carlo that generates supernovae based on a few model parameters, propagates the light according to a given choice of cosmology, includes astrophysical effects such as dust extinction and weak lensing, and incorporates instrumental effects such as K-corrections.

Instrumental effects are parameterized in terms of read noise, dark currents, point spread function, and calibration errors. For comparison with ground-based telescopes, the Monte Carlo also includes an atmospheric model with air mass and seeing effects. The result of the Monte Carlo is a Hubble diagram of corrected magnitude versus redshift. A cosmological fitter then extracts cosmological parameters from the simulated Hubble diagram for comparison with the generated cosmology. The fit cosmology tells us how well we can measure the science parameters of interest. An example of the output is shown in Figure 49, extracted from a publication on SNAP science.[7]

[7] C. Akerlof, et al., Supernova/Accelerator: A Satellite Experiment to Study the Nature of the Dark Energy, submitted to PASP

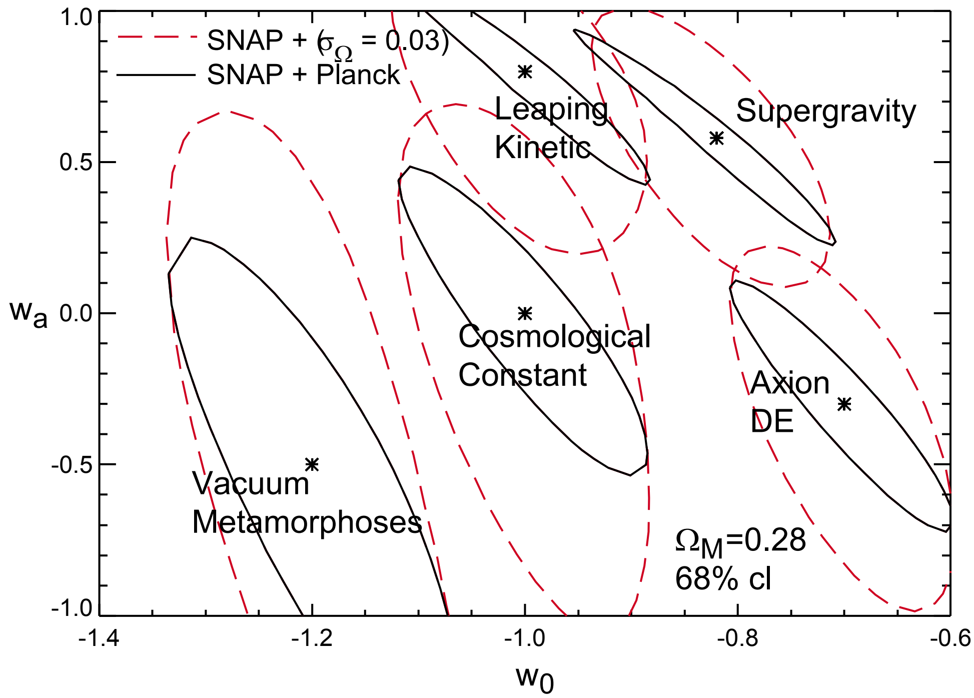

Figure 49. The confidence region in the dark-energy parameters for different fiducial dark-energy models representing very different physical origins: a cosmological constant, a supergravity model, vacuum metamorphosis, axion dark energy, and a leaping kinetic model. The larger ellipses are the results from SNAP and the smaller ones are for SNAP plus Planck. Note that $w' \approx w_a/2$.

The next step in the simulation R&D program will be to add the actual instrument emulation to produce pixel-level synthetic data. This synthetic data can then be fed to the analysis programs to extract the results. By contrast, the current version short-circuits the analysis by going directly to the parameterized result. To distinguish the two levels of simulation, we have dubbed the current parameterized version SNAP*fast* and we use the name SNAP*sim* for the in-development version with full instrument emulation. SNAP*sim* will be maintained throughout the mission, since it will be helpful in understanding the SNAP data as well as an aid in designing the mission.

The specific simulation R&D plan then consists of:

- Define the scope of the simulation by identifying the requirement studies that must be implemented. System parameters and deadlines are compiled from subsystem and project managers into a Science Requirements Studies Document. This requires minimal resources from the simulation group.

- Design and implement an architecture to support simulation activities. This subset of the full SNAP architecture satisfies the pressing needs of the simulation group. The design is developed by computer scientists after multiple joint meetings where the requirements of the scientist "clients" are established. The deliverables are first an Architecture Design Document and then the working architecture. Since

SNAP*sim* implementation cannot begin until the architecture is complete, these two items are critical-path deliverables.

- Design and implement the SNAP build and programming environments. The deliverables are a repository, programming standards document, programming documentation standards document, nightly build and testing mechanism, issue tracking, interactive development environment with plug-ins and hardware to house SNAP computing. Very little in the environment is SNAP specific so we leverage off the work of other experiments, e.g., Atlas, IceCube, SDSS.

- SNAP*sim* Release 1: Designing and implementing the SNAP*fast* functionality (parametrized simulation) in the new software architecture. This release will provide the framework, classes, and tools to perform mission requirements and optimizations for long-lead procurement items and for the ZDR and CDR. Release 1 must be available to initiate requirements studies and is thus critical-path. The delivery of the Simulation Design Document is the responsibility of a small team whose members have expertise in computing, supernova cosmology, astronomy, calibration, and HEP scientific computing. All programming resources will be assigned to its implementation.

- Performing the various requirement studies using SNAP*sim* Release 1. Based on their interests and expertise, simulation group scientists are given responsibility for individual studies. Priorities and resources are assigned based on the delivery milestones. The deliverables are defined in the Science Requirements Studies Document.

- SNAP*sim* Release 2: This extension of SNAP*sim* will provide pixel-level simulation tools for performing mission requirement studies that require image analysis for the ZDR and CDR. Image simulation is particularly for weak lensing science and the Weak Lensing Working Group is responsible for providing many of these packages. Our expertise in galaxy evolution and gravitational lensing combined with studies of instrumental behavior will enhance existing image-simulation software written by SNAP collaboratiors. This code will then be integrated into SNAP*sim*.

4.5 CDR Planning

The ultimate deliverable from the R&D phase is the CDR. The R&D plan presented here is designed to lead to a credible scope, cost, and schedule for the Ground Segment part of the CDR. Preliminary results are expected for the ZDR approximately one year in advance of the CDR.

It is important to note that, with the exception of the simulation, we do not plan to implement the Science Ops code during the R&D period. We will, however, develop preliminary designs for this code and pursue some implementation for the parts of the code identified as carrying risk in order to understand the scope, cost, and schedule as necessary for making a reliable estimate for the CDR.

Section 5. Telescope R&D

The design, fabrication, and test of a two-meter class space telescope is a project that can be expected to require four to five years, a time scale that places the Optical Telescope Assembly (OTA) work on the critical path for the planned SNAP mission. The R&D tasks associated with the OTA are therefore driven by two pressing objectives, both targeted at minimizing the risk of an OTA schedule slip: First, described in section 5.2, is the need to prepare a thorough specification of the OTA performance requirements, the OTA interfaces, and the OTA acceptance test plan, so that a comprehensive cost/benefit trade of alternative vendors and fabrication/test flows can be conducted prior to CDR. Second, described in section 5.3, because the primary mirror schedule drives the entire OTA schedule, we are pursuing an early decision on mirror blank material, design, and fabricator and intend to begin vendor evaluation studies, cost/benefit trades early enough to establish that all significant technology issues are solved well in advance of CDR. Moreover, our R&D schedule may allow the initial steps to be taken towards demonstration of a lightweight flightworthy technology demonstrator mirror blank. Third, described in section 5.4, is an overview of the continuing OTA risk assessment.

5.1 Pre-R&D Phase OTA Trade Studies

5.1.1 Trade 1: Optical configuration

Wide-field astronomical telescopes are not new. Beginning with the Schmidt survey telescopes deployed at mountaintop observatories during the mid-20th century, a variety of optical configurations have been proposed and many have been implemented. The usual goal is to achieve atmospheric-seeing-limited performance in visible wavelengths. For such uses, refractive correctors are suitable, and therefore many of these wide-field cameras utilize refractive elements at the entrance pupil (e.g., the Schmidt) while others use refractive field flatteners (e.g., the Sloan Digital Sky Survey instrument). SNAP, however, requires diffraction limited image quality, and operates over a much wider wavelength range, 0.35 to 1.7 μm. Refractive correctors cannot do this far more demanding job. Instead, to obtain a larger field than can be obtained with two-mirror Ritchey-Chretien optics and to achieve higher resolution than can be obtained with two-mirror Schwarzschild optics, one must explore telescopes that have three powered mirrors. Three-mirror wide-field telescopes have been discussed by many authors including Paul, Baker, Cook, Williams, Korsch, Angel, McGraw, Willstrop, etc. Most of these optical trains suffer from a large central obstruction in the pupil and from placement of the focal plane camera deep within the optical path. The obstruction leads to a significant loss of light gathering power and spatial resolution, and in space it is difficult to provide passive radiant cooling for the buried camera. Moreover, the Paul/Baker family of wide-field telescopes are unsuitable for long focal ratios. One configuration, originally proposed by Korsch in 1972, eliminates both these limitations through the use of a small secondary mirror, a tertiary mirror used as an inverting correcting relay, and of a focal plane located to one side of the primary optical axis where passive detector cooling becomes easy. For SNAP we have adopted this annular-field three-mirror anastigmat (TMA) configuration owing to these manifest advantages. In detailed studies during the pre-R&D phase we have found this TMA to be adaptable to a variety of lengths and focal ratios, allowing the diffraction pattern to be tailored in size for best science recovery.

5.1.2 Trade 2: Warm optics vs cold optics

It is well known that if the principal optical elements are provided with heaters and thermostats to keep them close to room temperature in their flight environment, the testing can proceed within an ordinary lab environment with no need to establish a variety of thermal test environments. For example, HST and FUSE were designed in this way, and mirror temperatures are maintained within a few degrees of 290 K on orbit. However, owing to nonzero thermal emissivity, the thermal background seen by an IR detector will depend on the temperature of the optics. For this reason, a near-IR instrument will have a lower noise level if its telescope optics are allowed to cool to an equilibrium temperature that is somewhat lower, below 270 K. This will occur naturally if no heat is supplied to a well-insulated optic viewing deep space. However, cold optics would require cryofiguring of the three powered mirrors, which has direct cost and schedule impact. During the pre-R&D phase, we explored emissivities of various mirror coating materials and found that protected silver offers the best reflectance throughout our critical NIR bands, and furthermore has sufficiently low emissivity that our predicted thermal mirror background will be below the zodiacal flux level provided that the mirrors are run below 290 K. Adopting a baseline temperature near 290 K will ease the mirror manufacture and test, yet not significantly impact the mission science.

5.1.3 Trade 3: Integrated focal plane vs separate focal plane instruments

It is well known that achieving a simple optical train (and a simple optical procurement specification) benefits from having a single input field and a single output field. Additional intermediate foci can be provided, but a cost is that the imaging performance of these fields may be strongly interdependent, and optical adjustments that furnish a good image at one focus may not furnish a good image at another focus. A particularly promising instrument concept, the Fully Integrated Detector Option (FIDO), places all SNAP sensors at a common focal plane, where they are tightly integrated and share mechanical structure, thermal environment, EMI environment, etc. The alternative is to have the various sensors located at distinct focal locations, with starlight delivered by pickoff mirrors and auxiliary optics. The total costs of the optical train, its testing, the instrument integration, and the flight operations scenarios all depend on this choice. During the pre-R&D period we explored these alternatives and adopted the FIDO option because it appears that all detector components can successfully operate at a common temperature and steps taken to simplify the optical system are certain to minimize the time spent on this critical path.

5.1.4 Trade 4: Low-CTE structure vs constant-T structure

During ground alignment and flight operations, it is vital to maintain precise relative positioning of our principal optical components in spite of environmental thermal variations. Two technical solutions to this problem are (a) the use of structural materials having nearly zero coefficient of thermal expansion, and (b) structural elements with a large CTE but maintained at a precise operating temperature by means of heaters, insulation, and high thermal conductivity links. During the pre-R&D phase we explored the use of various materials for the precision metering structure, and concluded that the strength, stiffness, manufacturability, and CTE of the best contemporary carbon fiber composites meet all our requirements. This decision allows a much-simplified active thermal control system. It is our present baseline choice for the metering structure.

5.2 OTA Specification Package

The R&D-phase endpoint of the OTA specification task is the completion of our Conceptual Design Report (CDR). This package will include engineering trade studies, cost/benefit analyses of the alternative acquisition, fabrication, and test plans generated and reviewed. Its focus, however, is the performance specification to which prospective vendors would be held if under contract. We are aware that over specifying or under specifying the component-level and system-level details will incur unnecessary costs and delays, and it is our intent to have our specification reviewed by an independent committee comprising experienced personnel from government and industry, as a condition for its release as part of a formal Request For Proposal. Reviewers will be asked to comment on the document's thoroughness, depth, clarity, and effectiveness.

We believe that four policies will materially streamline the OTA specification package and its use in communicating our needs to prospective suppliers of a complete OTA system or its components:

1. Our requirements will constrain the end-to-end optical performance, but allow a limited range of vendor-specific freedoms in choice of materials, technologies, processing, and optical test facilities. In this way we will capitalize on the unique strengths and experience of the successful vendor(s). For example, some telescope manufacturers routinely use vertical beam optical test facilities, while others prefer horizontal beam setups. Similarly there exists a variety of optical surface and figure tests, ranging from simple Hartmann masks through the most sensitive interferometric null tests, with variations that have been developed by each prospective vendor.

2. Our requirements will be finalized after careful consultation with optical design and fabrication engineers whose credentials have been established through broad industry recognition. Toward this end we have support contracts in place with individuals whose cumulative experience in large space optics is appropriate for a project of the scale of SNAP, and we will continue to strengthen our connections with industry by continuing contract work with prospective industry partners and suppliers.

3. Our requirements will be carefully prioritized with respect to potential tradeoffs that control the ease of manufacture, test, and integration. At present we are pursuing several trade studies discussed below.

4. Most telescope manufacturers are specialists. Some have particular expertise in mirror manufacturing while others excel in structure or integration. In addition, some NASA facilities have particular strengths in optical test and flight qualification work. Our procurement planning will therefore explore alternative routes: single prime vendor (with subcontracts) and combinations of suppliers and facilities. Our goal is to identify a route wherein the design, manufacturing, and test teams have the requisite experience to assure project success, while affording the customer sufficient visibility into the project's progress.

5.2.1 Performance requirements and draft interface definitions

Here we present an outline of the performance requirements and interface definitions that will be specified during the R&D phase. These specifications will be carefully reviewed by all members of the optics working group, and by a review board, prior to the scheduled ZDR and CDR project milestones. The finished requirements document will constitute our primary vehicle for communicating the SNAP OTA description to prospective vendors. Topics addressed will include:

1. Optical performance
   - Minimum effective aperture and throughput
   - Maximum permissible obscuration
   - Instantaneous field of view requirement
   - Strehl ratio at 0.63 μm wavelength averaged over field
   - Minimum ensquared energy for 10 μm pixels at 0.63 μm wavelength
   - Maximum allowed vignetting
   - Min and max effective focal length at final focus
   - Minimum throughput

2. Optical interfaces

   - Entrance aperture definition
   - Exit surface definition
   - Built-in test equipment illuminators & reflectors
   - Optical alignment features
   - Outer baffle intrusion limits
   - Inner baffle intrusion limits
   - Secondary baffle envelope
   - Cold stop intrusion limits

3. Mechanical interfaces

- Minimum and maximum mass, Center-of-Gravity, and Momemt-of-Inertia as appropriate
- Allowed mechanical envelope compatible with launcher and S/C
- Anticipated static and dynamic loads imposed by launch
- Allowed frequency ranges & Q-factors for response to vibration
- Location and orientation and tolerance of final focal surface
- Locations and orientations of OTA focal-equipment interfaces
- Locations and orientations of payload attach fittings
- Locations and orientations of electrical connectors
- Locations and orientations of ground support equipment (GSE) hoisting hooks
- Locations and orientations of shipping container attachments
- Locations and orientations of optical alignment GSE devices
- GSE wagon
- Specifications for in-flight adjustors for secondary and tertiary mirrors: range, stability, resolution
- Structural stability requirements imposed by optical performance specifications
- Specifications for ground alignment adjustors and 1-G support fixtures

4. Electrical interfaces
    - Voltages, currents, heater resistances, signal levels for thermal control system
    - Connector locations for OTA-supplied cabling & harnesses
    - Drive electronics plan for on-orbit mechanical adjustors
    - GSE connectors harnessing and sensors for ground thermal & vibration tests

5. Thermal interfaces:
    - thermal heat loads during ambient ground testing, if any
    - identify cryocooling requirements during ground processing & testing
    - thermal environment expected on orbit
    - static & dynamic thermal loads imposed by spacecraft, detector system, other loads
    - thermal profiles anticipated during optional detector annealing cycles
    - transient thermal/structural response imposed by on orbit attitude changes

As part of the OTA Requirements Document we have prepared a baseline optical system study that serves as an existence proof that our planned goals can be met. The present baseline optical system comprises a three-mirror anastigmat having a 2.0 meter aperture and an effective focal length equal to 21.66 meters, that decision being one of the trade studies identified below. The TMA layout is patterned after a family of analytic three mirror designs first explored in the 1972-1990 time frame. Its particular attractiveness for the SNAP mission is its ability to deliver a high quality image whose geometrical aberrations are 0.03 arc seconds rms blur, averaged over a large field of view amounting to about 1.37 square degrees. This baseline system, TMA63, is an all mirror system that requires no refractive correctors. Further details can be found at the SNAP website http://snap.lbl.gov where the current draft specifications and performance estimates are presented, and in two publications (Lampton et al., Proc. SPIE v.4849 pp.215-226 2002; Lampton et al., Proc. SPIE v.5166 #12, 2003).

5.2.2 R&D phase OTA trade studies

5.2.2.1 Choice of primary mirror material

A number of mirror materials have been chosen for the manufacture of large aperture space optics. The two leading examples for our application are:

- Corning ULE ™ (HST primary mirror and many others)
- Schott Glass Zerodur ™ (ORFEUS and SOFIA)

Each prospective mirror manufacturer and telescope vendor has particular experiences with these materials, and we anticipate that the right material for SNAP will depend on our vendor's favorable experience working his material efficiently. Studies already completed in the 2001-2003 time frame show that the ULE alternative offers less total mass and greater stiffness for a given aperture owing to the efficient closed-back geometry that it makes possible, and ULE has a far more extensive space flight history. On the other hand, the Zerodur alternative offers potentially quicker blank fabrication. Our choice will be decided on the basis of best value to SNAP, considering the entire tolerance budget, test cost, and overall schedule.

5.2.2.2 Telescope manufacturer capabilities

Determining the best route for procurement and test of the SNAP telescope is the single largest responsibility of the SNAP OTA team. During the pre-R&D period we visited a number of manufacturers of telescope optics and systems, and through a broad Request for Information we have received statements of capabilities from prospective vendors. During the R&D phase we are extending this work and exploring alternative routes for design, manufacturing, integration, and testing.

5.2.2.3 Total cost & schedule vs telescope wavefront error

Generally, cost and schedule requirements rise as allowable wavefront error is reduced, because additional cycles of measurement and figuring impose added labor. For this reason it is important to work closely with prospective bidders to better understand this tradeoff quantitatively and to identify the optimum specification for wavefront error.

5.2.2.4 Total cost & schedule vs primary mirror thickness

As a general rule, a thicker mirror is heavier but stiffer than a thinner mirror. Consequently a thicker mirror may take longer to fabricate and involve processing a larger amount of material, yet may provide considerable savings during the figuring, testing, and alignment phases of OTA production. These savings result from reduction or simplification of auxiliary 1 G support structures, air bags, etc. A further complication is that a heavier primary mirror creates added stresses in the OTA structural elements, influencing their size and strength requirements. These factors can best be understood by reviewing published analyses and performing finite element modeling for the primary mirror for a variety of potential lightweight structures, and assessing the degree of complication that thin and super-thin mirrors introduce. Preliminary efforts along these lines have already begun, and will be enlarged and extended under our 2004-2005 R&D plan.

5.2.2.5 Prototype vs proto-flight OTA metering structure

The metering structure that locates the principal optical elements is obviously critical in establishing the strength and stability margins for the entire OTA. It may be advantageous to build one or more prototype structural items to permit early proof testing, thermal expansion testing, vibration-table modal testing, and gravity load response determination. The alternative is to build an early flight model of the OTA structure, perform qualification tests using dummy mass components, and (when qualified) upgrade this structure to flight status and flow it into the integration process.

5.2.2.6 Preliminary test requirements and concept

A major consideration in scheduling and pricing a large space optic is planning the sequence of accept/reject tests that each element of the optic will undergo, and devising a fair policy to accommodate manufacturing deviations that may occur in finishing one element by the appropriate modification of the successive downstream elements. A clear test plan, carefully explained in the OTA requirements document, and supported by established industry manufacturing policies, is a high priority for SNAP. We intend to create a test plan for the SNAP OTA that offers flexibility to a prospective vendor in those areas that are non-critical, but that safeguard the key science driven requirements. Such planning will result from careful Q&A with established industry procurement consultants. This process has already begun. At present we are working towards a draft acceptance test plan that assures the performance of each telescope mirror separately, and then establishes the performance of the complete system through the use of both interferometric and direct-imaging techniques.

This plan will be elaborated during the R&D study to include specific requirements for performance, vertical/horizontal gravity de-loading, interferometer vs zone testing, full aperture vs partial aperture testing, accommodation of nonconforming optical elements, and the inclusion of one or more compensators into the design to allow for better control of focal plane position, image surface tilt, and other concerns.

5.2.2.7 Draft integration/test flow sequence

Much of the ongoing test planning is built around a nominal overall sequence for the integration of the entire mission. This sequence is divided into levels, distinguished largely on the basis of facility requirements since each level has an associated suite of tests to be performed:

Level 6: The tested/coated telescope mirrors and the flight metering structure are integrated with the built-in optical test equipment (BITE) and the optical GSE. The end-to-end telescope performance tests are conducted.

Level 5: The telescope is integrated with the instrumentation suite: array imager and spectrometer cryostat, auxiliary guide star trackers.

Level 4: The telescope is integrated with the outer baffle and aft closure.

Level 3: The payload is integrated with the spacecraft bus.

Level 2: The complete spacecraft undergoes qualification testing: electro-magnetic compatibility, thermal vacuum, and acoustic/vibration.

Level 1: The spacecraft is integrated with the booster and launch shroud.

5.2.2.8 Prospective OTA vendors

Because the success of the OTA procurement for SNAP hinges on prompt effective participation by an industry partner, it is reasonable to ask which potential industry leaders are known to have the necessary experience and facilities to allow this project to precede efficiently. In consultations with other space astronomy groups we have identified a small number of potential vendors who can manage all or part of the OTA project as we have envisioned it.

5.3 SNAP Technology Mirror

The R&D phase of the SNAP Technology Mirror task will accomplish as much risk reduction as possible given the resources available during R&D. These subtasks include:

a. A comprehensive specification for the primary mirror, including performance, thermal environment, cost/benefit trades, mirror materials trade;

b. Assessment of industry readiness and ability to accommodate our resource allocation limitations during the R&D phase;

c. Sufficient visibility into our optical acceptance test plan that mirror related issues can be safely decided.

Towards these ends we have been aggressively pursuing suppliers within industry to obtain current cost and schedule estimates for the most attractive alternative primary mirror (PM) configurations. Estimates have been obtained during 2002-03 and an additional study in 2004 will provide further guidance. We have also pursued a series of refined FEMs, coordinated with mirror blank manufacturers, to ascertain the margins of safety and the gravity-induced surface deflections that will be dealt with during mirror and system acceptance testing. We are confident that either Corning ULE or Schott

Zerodur material can be used to produce a satisfactory PM for SNAP, but the better alternative will be chosen on the basis of the best overall value to the program.

5.4 OTA Risk Assessment

We have identified several potential risk areas in the procurement of the OTA. Briefly, the ones we have examined so far are the following.

5.4.1 Mirror fabrication/test risks

Any large glass item poses a potential risk of damage or fracture during ground handling, grinding, polishing, and testing, particularly where there may be extreme environmental tests performed using thermal stress, vibration, and mechanical shock. Fortunately, large astronomical telescope mirrors have been safely prepared and handled for projects far more demanding than the SNAP telescope optics. We are assured that a two-meter class telescope does not pose unusual risks, particularly when experienced optical manufacturers are brought on board to manage the production.

One risk area is the possibility of serious figuring errors being introduced into one or more of the SNAP telescope optics. We plan to guard against this by implementing (as a minimum) a four-stage test plan in which each mirror element is tested individually, and then in concert as the OTA is assembled. We understand that this progressive test plan, finishing with full aperture end-to-end test performance while mounted in the flight OTA structure and supported appropriately against 1 G deformations, provides the needed assurance that a manufacturing fault will be discovered before the SNAP mission is launched.

Does the launch stress environment pose a threat to the OTA? A number of two meter class telescopes have been safely launched using industry-proven three point support systems. These mirror support structures are fully qualified for optical elements in our mass class and have proven themselves on a variety of missions. We intend to capitalize on this experience and adopt proven structural mirror support methods for the SNAP mission. Our draft specification currently specifies kinematic flexure bipods affixed to the PM rear surface at the 70% radius location since our FEM analyses show that this mount configuration offers the lowest peak launch stress.

Can the thermal environment pose a threat to the on-orbit OTA performance? We believe that by implementing a comprehensive thermal-vacuum test plan we can quantify the thermal performance of the OTA prior to flight. In addition, we anticipate that judicious use of *in situ* electrical heaters and thermostats will allow us to understand, and overcome, any reasonable thermal off-nominal situations. A preliminary thermal budget for the PM, for example, indicates that approximately 20 W steady radiation to the outer baffle and to deep space will be balanced by a similar wattage of electrical heaters carried on the rear (convex) surface of the PM.

5.4.2 Mechanical structural risks

Any large mechanical structure loaded with a ton (or more) of equipment may fail in a variety of ways when presented with the acceleration and vibration environment of a space launch. We plan to mitigate these risks by adopting a comprehensive plan for piece part testing and for qualification of materials, processes, and finished structures. In the aerospace industry it is common to perform static and dynamic load testing to establish measured safety factors for the mechanical elements of the OTA. In addition, TMAs have 13 adjustments for focus and collimation, a subset of which are to be motor-driven on orbit. The motorized actuators for these adjustments will require their own qualification and test program during the fabrication phase of the SNAP project. We anticipate preparing a finite element analysis of the principal flexural modes of our adopted OTA structure, and computing the expected loads and margins for a variety of launch environments, to better understand the tradeoffs associated with the alternative structural concepts.

5.4.3 End-to-end performance risks

A key issue with regard to acceptance testing is the fact that all acceptance tests are necessarily performed in a 1 G environment, while the only performance that affects the science is the performance that is manifested in a 0 G environment. For this reason we anticipate the need for careful planning with regard to the de-loading of the principal optical and structural elements. In particular, a lightweight primary mirror is certain to deform significantly unless it is designed with extremely high stiffness, particularly in the azimuthal deflection mode. An obvious trade is to compare the expected deflections for various mirror thicknesses, stiffness, and cost, while factoring the test plan complications that arise from the 1 G test environment. It is anticipated that full-aperture end-to-end testing will be required, performed interferometrically, by null test, or by zonal test. We plan to also perform imaging tests on the complete OTA using an autocollimation setup and a test flat; gravity unloading will be mandatory for this test. With a full understanding of these important cost and schedule drivers, the SNAP team has begun to assess various gravity unloading strategies and associated test plans using FEM techniques.

5.4.4 Schedule delays owing to requirement revisions

The OTA delivers its image to a science instrument package, and the details of the final focal surface (plate scale, field, focus position) drive the telescope design. By the time that bids are sent to prospective vendors we expect that our exact image requirements will be fixed. During the R&D phase, however, changes in this instrument package may occur. We intend to provide the manpower necessary to track instrument revisions and maintain the OTA requirements document in an appropriately updated manner.

5.4.5 Manufacturing error budgets

The manufacturability of the OTA will depend on an appropriate manufacturing error budget, in which a variety of potential error magnitudes from figuring, fixturing, assembly, and test are correctly distributed. These decisions will hinge partly on the experience of the optical fabrication partner chosen and partly on the judgment of our OTA team members. We intend to create a preliminary manufacturing error budget as part of our OTA Requirements Document, and invite prospective vendors to comment on our assessment and/or provide alternative error budgets based on their experience. In this way we intend to be flexible with regard to individual error terms yet remain relatively inflexible with regard to the overall performance requirements.

5.4.6 Contamination control

During manufacture, test, shipment, integration, and launch the OTA will be subject to a number of potential contamination hazards. We intend to develop a contamination control plan in concert with our OTA supplier that will safeguard the cleanliness of the optical surfaces during all phases of the program.

Section 6. Spacecraft R&D

Major science instrument driven requirements on the spacecraft include the provision of:

1. Structural support between the instrument and the launch vehicle attach ring,
2. Power to operate the instrument as well as spacecraft functions,
3. A communications link for commands to the instrument an for the downlink of engineering and science data,
4. A system to point and hold the instrument steady for viewing of science targets,
5. A propulsion system for orbit insertion, station keeping, angular momentum control, and observatory end of life disposal.

The thermal environment of the SNAP telescope and instruments will be controlled through a combination of passive and active thermal management included in the instrument, e.g., radiators, baffles, shields and heaters. The spacecraft will have an adiabatic interface to the instrument and will control its temperature through radiation from its outside surface. Two spacecraft attitude control system components, the star trackers and the inertial reference units will be mounted on the Instrument optics bench and will be thermally managed by the Instrument. Similarly, two instrument components, the observatory control units and the instrument memory units will be mounted on the spacecraft and will be thermally managed by the spacecraft.

The SNAP Instrument team has completed a strawman conceptual design of a possible SNAP spacecraft. We believe that a spacecraft comprised of industry standard components using industry standard interfaces between the spacecraft components and between the spacecraft and the instrument will meet all instrument derived requirements. The most difficult requirement, that of meeting the need to point and hold the telescope steady for the science observations, is defined in SNAP drawing 00007-PP02-A. A study was performed by an aerospace systems vendor using a mechanical mathematical model of the observatory developed by the SNAP project along with a modified version of the ACS system developed for the Kepler spacecraft. Their conclusion was that a system using standard mid-price range components taking data from the star guider system built into the telescope would easily meet the SNAP requirements.

The intent of the SNAP project is to contract with a single aerospace industrial contractor who would supply the spacecraft portion of the observatory system as an integrated package. This vendor may perform all or a portion of the task of Integration and Testing between the spacecraft and the instrument. The primary spacecraft-related task during the R&D period is to clearly define the science driven requirements on the spacecraft system, and to delineate exactly what is included in the spacecraft portion of the task.

We intend to utilize the Goddard Space Flight Center’s Rapid Spacecraft Development Office (RSDO) or the standard RFP process to select an industrial teaming partner for

SNAP during the time between CD0 and CD1 or just after CD1. While the spacecraft in the RSDO catalogue are fixed in price, we are aware that SNAP requirements will require significant tailoring of spacecraft systems, particularly the mechanical structure which must be a custom design. Thus, we intend to work with the RSDO spacecraft contractors to develop a more detailed strawman design together with a detailed cost and schedule to support the CDR prior to CD1.

During the R&D phase we will continue with trades and analyses intended to aid in the development of a clearly defined set of requirements on the spacecraft system. Thereafter we will be in a position to select a teaming partner to work on the spacecraft strawman design and develop a detailed cost in support of the implementation phase. Below we describe the spacecraft-related analyses and trade studies which will be continued during the R&D period. Several aspects of the spacecraft, such as structural and thermal design, are also discussed in Section 7, R&D System Engineering.

6.1 Spacecraft Related Analyses and Trade Studies

6.1.1 Observatory structural design

The design of the observatory primary structure is strongly constrained by payload requirements including maintenance of the OTA alignment, payload thermal control, and a requirement for modularity to allow the instrument to be assembled and disassembled for testing and trouble-shooting. This leads to the use of a custom observatory structure design driven by payload requirements rather than the use of a "standard spacecraft bus" which undergoes minor modifications to accommodate the payload. The SNAP spacecraft structure will include a load bearing structure which connects to the launch vehicle attach ring and a tie point to the payload which transfers the entire payload reaction to the launcher. The structure must also include mounting area for the spacecraft avionics and propulsion components. A relatively detailed observatory design is required to settle the question of what form the spacecraft structure will take, and is also needed before the thermal design can be completed.

A less obvious but very important requirement is that the mechanical layout be closely iterated with the integration and test plan so that sub-assemblies can be removed for testing and debugging without disturbing portions of the system that already have been tested and installed.

These issues are discussed in more detail in Section 7, R&D System Engineering.

6.1.2 Attitude control system (ACS) preliminary system design and error analysis

Attainment of 0.02 arc-second rms pointing stability of the telescope is essential for the full completion of the SNAP mission science goals. While pointing accuracy at this level and better has been accomplished on a number of previous spacecraft, (e.g., Hubble at 0.005 arc-seconds with a significantly less rigid structure and the Remote Mirror Experiment) this requirement is at the high end of standard spacecraft practice. We have recently completed an industry study which shows that a viable ACS solution using standard components exists for the particular mechanical properties and disturbance sources of the SNAP mission.

We have also created a computer model of the SNAP ACS system. In work completed we have concentrated on static performance, creating a dynamic model including ACS feedback with Kalman filtering. We have integrated wheel dynamic noise disturbance spectra, and included FEM structural resonances. We will continue and refine this model during the FY04 R&D program. We will concentrate on dynamic performance, upgrading the computer model to include telescope flexural behavior, installing a simplified fuel slosh model, exploring large angle settling behavior, and estimating maneuver times required for model mission profile. The inputs to the model will be continuously updated throughout the program as the designs of the various sub-systems are refined.

The model will determine the attitude determination capability with and without attitude information from the Optical Telescope Array (OTA). In this way we will develop an understanding of the relation between the requirements on the OTA star guider system (e.g., update rate) and the ultimate pointing capability of the integrated observatory system.

6.1.3 Propulsion system specification and analysis

The SNAP spacecraft will use a monopropellant hydrazine system to unload the reaction wheels used by the ACS system and to meet the NASA debris requirements. Since the requirements on this system are well defined and easily met, this system is not expected to be a risk area or one requiring any technology development. However, portions of this system interact with other systems in the observatory in ways that have a bearing on the successful operation of those systems. In particular, slosh in the propellant tanks could have a significant effect on the operation of the ACS system, and mechanical properties of the thrusters and their associated plumbing may significantly impact the modularity and testability of the observatory.

For this reason we will create a propulsion system concept and generate a set of specific tanks, thrusters, valves, and plumbing to be used on the SNAP observatory. From this we will generate mechanical models of the tanks to be used in the ACS model.

6.1.4 Power system components specification

Since power system technology is very well developed, the system is a low risk area and will use components with a long history of space flight use. What is usually the most difficult part of the power system, the solar array panels, is relatively straightforward for SNAP because the payload thermal system will provide a large area that is always pointed within 45 degrees of the sun. The thermal design task will include the provision of flat areas for mounting solar cells with suitable capability for dumping waste heat. During the R&D phase we will refine the power estimates and service requirements and then refine the strawman power system design to develop detailed requirements on the control unit.

6.1.5 High gain antenna and gimbal specification and analysis

The RF performance requirements for the High Gain Antenna (HGA) have been analyzed as part of trade studies with the ground systems and orbit analyses. These trades will continue to refine the size of the steerable antenna needed to communicate SNAP data to the ground at high rates.

The detailed mechanical properties of the HGA and its associated gimbal assembly are a required input for the ACS model. During the R&D phase we will identify manufacturers for these units and determine their mechanical properties for use in the ACS model.

Section 7. System Engineering R&D

SNAP System Engineering is responsible for the coordination and management of all design and engineering activities involved in the development of the SNAP Observatory. The task is to insure that the spacecraft, telescope, instrumentation suite and ground data system form an integrated and consistent design that will successfully meet the requirements placed on the project.

During the R&D phase, the primary engineering activity is to select and refine a conceptual design approach for the observatory and mission that will meet the SNAP high-level mission requirements, and to perform design and systems trade studies to optimize the baseline approach. Our intent is to concentrate effort in those areas requiring the greatest innovation or posing the greatest potential risk, and to postpone the development of detailed plans for activities that routinely have been accomplished on previous missions.

7.1 System Engineering R&D Studies

7.1.1 Structural design studies

The design for the observatory structure requires the establishment of an initial set of requirements imposed by the telescope and instrumentation suite. This design is in progress, and will be continue throughout the R&D phase. The design approach is to start with the primary metering structure that supports the 3 mirrors and flat of the TMA plus the instrument's focal plane assembly. This will then be integrated with the needed supports for light baffles and thermal shrouds, including the load paths to the launch vehicle interface ring via the spacecraft bus. Finally, the generic accommodations will be included for the instrument electronics modules and the many needed spacecraft components. The solar array will be mounted on the warmer side of the large stray light baffle that is always oriented roughly perpendicular to the sun.

An additional task of the observatory structure design study will be to refine the extent of the "spacecraft" portion of the observatory. A focus of this task is to refine the spacecraft's primary structural role in supporting the observatory, while also retaining reasonable implementation flexibility for the aerospace industry teaming partner, as part of the spacecraft procurement.

Mathematical models of the structures will be developed in parallel with the structural design concepts, and will also be used to support the thermal design, and ACS analyses, as well as verifying the adequacy of the structure.

The layout, design, and analysis will be done by a team of SNAP engineers.

7.1.2 Thermal design studies

The thermal control task is closely related to that of the structural design, so activities in both areas will proceed in parallel with continuing interaction reviews. Thermal control is of extreme importance for the proper operation of the observatory, particularly in three areas:

- The maintenance of the figure and focus of the OTA;
- The maintenance of the desired operating temperature of the focal plane sensors and control of stray radiation into the IR sensors by nearby structure;
- The reduction of potential thermal disturbances that might compromise the pointing capability.

To address these critical issues, we will develop the detailed thermal models, including their needed control systems. This task will include development of the control strategies, design of structural element coatings, viable thermal isolation concepts, heat strapping, etc., followed by modeling of this complete system. Given the sometimes less rigid nature of baffles, shields, and thermal isolators, the mechanical properties of those design choices will be a needed input for the structural, and perhaps ACS models. We will also develop a layout for the solar panels that maintains the cells in their acceptable operating temperature range.

By the end of the R&D phase, we expect to have a design concept with sufficient detail to develop the mathematical models of the system that will demonstrate the routine observatory operation meeting the SNAP mission requirements.

7.1.3 Attitude Control System (ACS) design studies

The key ACS feature, needed to achieve SNAP's precise pointing requirements, is the baselined "through-the-telescope" pointing determination that is achieved with high speed video CCDs mounted on the focal plane. The complete attitude determination calls for supplementary information from star trackers and a gyro. The Kalman filtering techniques smoothly blends the sensor inputs in an adaptive manner that will minimize image jitter.

A detailed ACS modeling effort is being directed by Prof. David Auslander, a pioneer of modern state space control theory. Both ground up physical models and also state variable models (using NASA's Treetops software) are being developed as an ongoing cross check. Sensor (e.g., photon counts, IRU drift) and actuator (momentum wheel rumble) are included with significant fidelity. Spacecraft disturbances, in the form of flexible body dynamics, fuel slosh, and shutter motions will also be included in these studies. Strategies for the Kalman filtering processes are also an important part of these studies.

7.1.4 Payload and observatory integration and test plan

Because of the stringent pointing requirements on the SNAP telescope and the fact that the system will be designed to work in a zero gravity environment but must be tested in a 1 G environment, the I&T task will be at least as challenging as that of the design and fabrication of the observatory. The I&T plan is driven first by the requirements of the OTA manufacturing and testing, and second by the assembly and test of the integrated science payload including the focal plane sensors. Because the OTA components provide the major testing challenges, the OTA team will develop the I&T plan outline.

During the R&D phase, manufacturing and test plans for each candidate mirror fabrication process will be developed. Methods of performing each required test will be identified, and a plan will be developed that includes the identification or design of the facilities required to accomplish the tests. We anticipate that dedicated custom equipment will have to be developed which may include modification of existing facilities. An important part of the process will be an evaluation of what tests can practically be done, and in what areas we must rely on analysis (e.g., how can we fully test the attitude control system?).

By the end of the R&D phase we will have a definition of each of the optics related tests, the order in which they will be done, a definition of all manufacturing and assembly steps, and a preliminary definition of the facilities requirements and an evaluation of possible ways to acquire them.

7.1.5 Mission analysis and orbit-debris strategy

A key element in the SNAP mission strategy is to provide a suitable platform from which the science measurements can be made using a readily available launch vehicle. We currently plan to use a highly elliptic, 3-day orbit which will be synchronized so that the perigee over earth is centered about the primary ground station. This is achievable by a several available launch vehicles.

Since this orbit crosses the orbit of geosynchronous satellites, the mission may be required to de-orbit in less than 25 years. During the R&D phase, we will determine the best approach to satisfying the orbital debris requirements.

At the end of the R&D phase we will have a baseline orbit definition, and the related set of requirements for ACS, propulsion, data and command systems needed to support the orbit insertion. Any impacts on the ACS system will be iterated into the parallel ACS modeling efforts.

7.1.6 Launch vehicle requirements

The refined definition of the observatory structure, mass, pointing requirements, and orbit analysis developed by the System Engineering activities performed during the R&D phase will result in a further understanding of the requirements on the launch vehicle. We will use this information to make a preliminary selection and to initiate preliminary discussions with the vendor regarding availability and cost.

7.1.7 Reliability analysis

During the R&D phase the System Engineering group will develop the first order failure modes and effects analyses for the observatory, with emphasis on development of a plan for the use of redundancy and elimination of single point failures. This information is essential to properly specify requirements on the spacecraft and to guide the layout of the payload electronics and data system. This activity will be done primarily by SNAP engineers with assistance from outside consultants.

7.1.8 System engineering tracking documents

During the R&D phase we will set up a Configuration Control system for the project and initiate a formal system for the tracking of mechanical, electrical and thermal properties of each component and subsystem. We will also set up systems for tracking computing, data and memory requirements.

Section 8. R&D Phase Management

Proper management and systems engineering activities are crucial to the development of a good project concept and implementation plan. Proper technical and organization groundwork during the concept phase will make possible the straightforward and effective implementation of the project and enhance the probability for mission success.

Management plays a supportive role in R&D, providing resources as needed to accomplish an agreed-upon set of research tasks. In contrast to development phases, management neither dictates the schedule nor demands strict adherence to a specific budget. Rather, management works with the PI, Systems Engineering and R&D developers to prioritize those results that can be obtained for the project with reasonable overall cost and appropriate schedule. It is management's goal to achieve the lowest possible mission risk by thoroughly investigating new technologies and assessing their readiness before proceeding into fabrication.

In parallel with the R&D activities, SNAP management is responsible for coordinating the scientists and engineers in the development of the SNAP project concept, in determining its schedule and its implementation cost. These tasks are further defined below. The groundwork is prepared for successful project execution during the conceptual design phase.

8.1 Management Elements

Project management during the conceptual design phase is carried out by the Project Directorate, including: advisory bodies, the Systems Engineering Office, and the Project Office.

8.1.1 The Principal Investigator

The Principal Investigator / Project Scientist has principal responsibility for the project with regard to its scientific mission. The Principal Investigator (PI) is the spokesperson for the R&D project and oversees the scientific planning. He leads the activities of the collaboration, the scientific working groups and receives advice from the Institutional Board. The PI will maintain frequent contact with the members of the Institutional Board, from whom he will obtain advice on all major collaboration issues.

8.1.2 The Project Directorate

The body responsible for technical, scope, schedule and cost execution of the project is the Project Directorate. It consists of the Project Director, the Project Manager, and the Deputy Project Manager. The Project Office and the Systems Engineering Office assist the Project Directorate in this regard. The Project Directorate works closely with the Principal Investigator to maximize the scientific return of the project.

The Project Director has responsibility for the direction of SNAP project activities. The Project Director coordinates the R&D, conceptual design process, and works closely with the Principal Investigator to ensure the scientific success of the project. On financial matters, the authority of the PD will be consistent with the requirements of the funding agencies and will include responsibility for keeping the agencies informed about the status of the project.

The SNAP Project Manager (PM) is responsible to the PD for the execution of the project within the schedule, cost and resource constraints available. With support from the Project Office (PO) and the Systems Engineering Office (SEO), the PM will establish tasks, work statements, Memoranda of Understanding (MOU), deliverables, schedules, and changes to those elements.

The PM is responsible for day-to-day project management, including: project status, risk management, documentation, cost and schedule tracking, subcontract management, and coordination with team members. The PM is the focal point of communication for project construction.

The PM will be responsible for establishing a baseline project plan. This plan will establish the schedule, cost phasing, and resource needs to carry out the SNAP project consistent with experiment science requirements. This proposal is the first step in defining the project plan. The complete project plan requires the approval of the PD and the agencies before being accepted as the baseline.

The SNAP Project Systems Engineer (PSE) is responsible to the Project Manager and Project Director for the engineering of the project and the organization and management of the engineering resources. The PSE is responsible for the development of cost and schedule and the optimization of the project through the Systems Engineering Office (SEO). The PSE will establish specifications, requirements, interfaces, and work statements, and is responsible for overseeing configuration tracking as appropriate during the conceptual design.

8.1.3 Management Panel

The management of SNAP currently is composed of scientists and engineers from both the University of California Space Sciences Laboratory (SSL) and from Lawrence Berkeley National Laboratory (LBNL). In order to permit the efficient functioning of the management team and provide a unified approach to oversight and access to resources, and to enhance communication, the two institutions have formed a Management Panel for SNAP. Currently serving on this board from SSL are: Prof. Robert Lin (Director SSL), Henry Heetderks (SNAP Project Manager), and David Pankow (SNAP Systems Engineer). Serving from LBNL are Saul Perlmutter (SNAP Project Scientist and PI), Michael Levi (SNAP Project Director and Co-PI), Pier Oddone (Deputy Director LBNL), Jay Marx (Project Integration & Management Officer), Prof. James Siegrist (Physics Division Director), Richard DiGennaro (Deputy Project Manager). This board currently meets weekly to discuss joint organizational and planning issues.

8.1.4 Institutional Board

The SNAP Institutional Board is composed of a lead scientist from each of the collaborating research institutions. The Institutional Board assists the PI in establishing scientific goals and objectives of the SNAP project. It advises the PI on all collaboration and collaborating institution matters of the project. It will develop a policy for membership and for publication. The Board will decide on controversial issues within the collaboration by consensus or by voting.

The PI and the PD chair the Board. Official Board meetings will be held on an as needed basis and no less frequently than twice a year.

8.1.5 Project Technical Board

The SNAP Project Technical Board (PTB) is responsible for working with and advising the Project Directorate with respect to the execution of the project as a whole. Its membership consists of the PM and PSE, leads from the Systems Engineering Office, the Project Office, the Safety, Quality, and Reliability Office, the individual systems managers, and additional members as deemed appropriate by the Project Directorate.

The PTB shall meet on a regular basis to discuss technical, cost and schedule issues and will form the basis of the Change Control Board (CCB). Its main goal is to help ensure that all systems of the project are being adequately integrated and executed toward the scientific and technical goals of the project within the constraints of budget and schedule.

8.1.6 Systems Engineering Office

The Systems Engineering Office (SEO) is charged with developing and maintaining the system hardware and software requirements and specifications. The SEO reports directly to the PSE within the SNAP Project Directorate. The SEO has responsibility for system level issues. During conceptual design, the SEO primarily will be concerned with top-level requirements flow-down so that design and planning decisions are made with overall systems considerations in mind. Its other key role is the development of interfaces between the various systems. As such, the SEO will be working continuously with system managers to ensure that interfaces are properly defined and that technical issues affecting more than one system are resolved efficiently and effectively.

Requirements, specifications, and Interface Control Documents (ICD) will be entered into configuration management by the end of the conceptual design phase. Systems management will be performed through regular reviews of the design activity.

8.1.7 Project Office

The Project Office (PO) is responsible for monitoring the technical scope, cost and schedule performance of all portions of the SNAP project and providing assessments to the Project Directorate. The Project Directorate then provides timely and complete reports to the sponsoring entities. The Project Office will maintain the SNAP master resource-loaded schedule that is capable of determining and monitoring the progress of the project.

8.2 Management Processes

Beyond day-to-day oversight of the R&D program, the main activities of the management group and systems engineering group include requirement specifications and development, development of collaboration agreements, systems engineering, oversight of cost and schedule development, risk assessment, and generation of regular progress reports. Each of these areas is discussed below, followed by a summary of the major milestones and deliverables during the conceptual design phase.

8.2.1 Requirements and specifications development and control

A top-level project scientific requirements document will be developed during the initial phase of the program by the project science team. Systems requirements and definition are the responsibility of the Project Systems Engineer and the Systems Engineering Office. The SEO will lead the definition of lower level system and subsystem requirements using a documented flow-down process. All hardware and software elements of the SNAP system will be defined in these specifications. At the appropriate point in the program, the specifications will be placed under configuration control, after which changes will be made by means of formally controlled Engineering Change Orders (ECO) that assure proper review by all affected project elements. Updated documentation will be made available to all affected parties. A straightforward system of verification of the latest current version of any project document will be continuously maintained and readily accessible to all.

8.2.2 Management of collaboration agreements

Memoranda of Understanding (MOU) will be written between the institutional members of the SNAP collaboration and the Project Directorate. These agreements will cover the cost, schedule, and technical scope of deliverables, and resources to be provided by respective collaborators and the resources to be provided by the Project Directorate. The MOUs will specify inter-institutional conduct within the collaboration as well as the scope of efforts for the respective collaborators. The MOUs will be reviewed along with progress each year as part of the yearly financial planning cycle.

The members of the SNAP collaboration will subcontract to LBNL, or, if required, to UCB. The subcontract will be established by means of a proposal that contains a statement of work, technical requirements, specifications (where appropriate), schedule, and cost of elements of the deliverables. A subcontract manager affiliated with the SNAP project office will monitor progress and serve as the point of contact for contractual matters between the project office and collaboration institutions. The subcontract manager reports to the Project Manager.

8.2.3 Management and performance of systems engineering

The SNAP Project Systems Engineer has primary responsibility for assessment of all systems-level issues (the Project Director is ultimately responsible for decisions, with input from the PI). It is critical in this process to view all elements of the SNAP project as a combined entity and to properly allocate requirements and design approaches across the entire system. As part of the conceptual design study, the Project Systems Engineer will develop a Systems Engineering Management Plan that will serve as the framework and control for all subsequent work and trade-offs. The evaluation criteria for examining the trade-offs will be developed during this same phase, very early in the design process. Additionally, the SEO will be primarily concerned with the development and analysis of top-level requirements and their flow-down. Systems models will be developed and the initial trade studies will be performed. System operation will be considered so that design decisions are made with the end user in mind. The other key role of the SEO is in the development of interfaces between subsystems. As such, the SEO will work continuously with system and subsystem managers to ensure that interfaces are properly defined and that technical issues affecting more than one system are resolved efficiently and effectively. An important product of the initial phase is the establishment of initial system architecture and initial subsystem interface definition.

8.2.4 Cost and schedule development

During the conceptual design phase, several critical activities must occur. The SEO management plan must be developed. The requirements development and analysis must be started and the appropriate evaluation criteria must be identified. A number of important trade-off studies must be performed and analyzed, as they will determine basic aspects of the system. The risk management plan with ties to the R&D plan needs to be developed and implemented. The initial system architecture and interface definitions must be established.

During the conceptual design phase, the initial R&D and technology plans must be perfected and executed including the necessary prototyping efforts and associated test plans. The engineering concepts must be developed, and prototype development and tests must occur. Also crucial during the conceptual design is the development of the detailed R&D plans that extend beyond the conceptual design phase into the preliminary design phase.

Additionally, the SNAP Project Office will develop the management and staffing plans; MOUs between collaborators for the R&D phase; the complete Work Breakdown Structure (WBS); the cost estimates; and the integrated schedule.

With the movement into Conceptual Design, activities shift from a definition and exploratory phase to one on concerted systems, project, and technology design and development. The conceptual design of all subsystems is completed and a Conceptual Design Report is reviewed. The final technology and development plans with milestones and decision points are completed.

Within the SEO and PO areas the system architecture is finalized. The subsystem requirements are assigned. The subsystem interface definitions and formal risk analysis are completed. The configuration management and change control plans are finalized and implemented. The final project planning, system safety, reliability and quality assurance plans are completed. The cost estimate (cost bracket), contingency analysis, master resource loaded project schedule, and WBS are completed and prepared for review.

During conceptual design, the acquisition strategy is prepared. This strategy sets forth the management approach that will be used to ensure that the project contract or system of project contracts satisfies the approved mission need. The acquisition strategy can be part of the mission need document, a separate document, or a part of the Acquisition Plan.

8.2.5 Risk assessment

The first step in the management of risk is its assessment. This is done initially in conjunction with the estimation and determination of the work to be done. Each element used in costing is assessed and scored as to its stage of development and potential impact on the project. Specifically, each element is rated for design/approach maturity, complexity, dependency, technical development, cost uncertainty, and potential schedule variance.

The data thus obtained are then scored following procedures adapted from previous large H.E.P. project and NASA approaches. Calculations are then done on the assessed risk score to determine an appropriate level of cost and schedule contingency. In parallel, possible scope contingencies are identified with decision points established where technical trade-off choices must be made.

Once the project is under way, issues identified with risk to the project are monitored and contingency is allocated where necessary. In addition, reliability assessments and trade-off studies also seek to minimize incidental as well as project risk. It should be stressed that risk management is not merely the initial allocation of funding contingency to various tasks and subtasks. Complete risk management is an ongoing effort throughout the life of the project and involves developing not only the funding contingency but also the schedule and technical contingencies.

8.2.6 Progress reports

Financial and project reports will be submitted to the funding agencies as required. Technical progress reports will be submitted to summarize progress, concerns, problems, changes, and plans for the next period. In addition, frequent contact with the agency technical monitors will be the project's standard practice.

8.2.7 Activities

Key activities during the conceptual design phase of the project are:

- Perform project & detail design phase technical and programmatic risk analysis
- Develop system-level functions and requirements
- Identify long-lead procurements
- Develop project execution plan for preliminary design
- Set project execution strategy
- Review design alternatives
- Identify project standards and procedures
- Develop preliminary design phase budget and schedule
- Develop total project cost and schedule range
- Identify current and two fiscal year funding requirements

8.2.7.1 Major reviews

Major reviews are:

- Draft Requirements Review
- Conceptual Design Review

8.2.7.2 Major deliverables at CDR

Major deliverables at CDR are:

- Acquisition Plan
- Project Expectations Summary
- Statement of Work
- NEPA Documentation
- Systems Engineering Management Plan
- Conceptual Design Package
- Preliminary Project Execution Plan
- Preliminary Hazard Analysis Report
- Preliminary Team Execution Plan
- Risk Management Plan
- Preliminary Design Phase Budget & Schedule
- Verification of Mission Need
- CDR Package
- Total Project Cost & Schedule Range

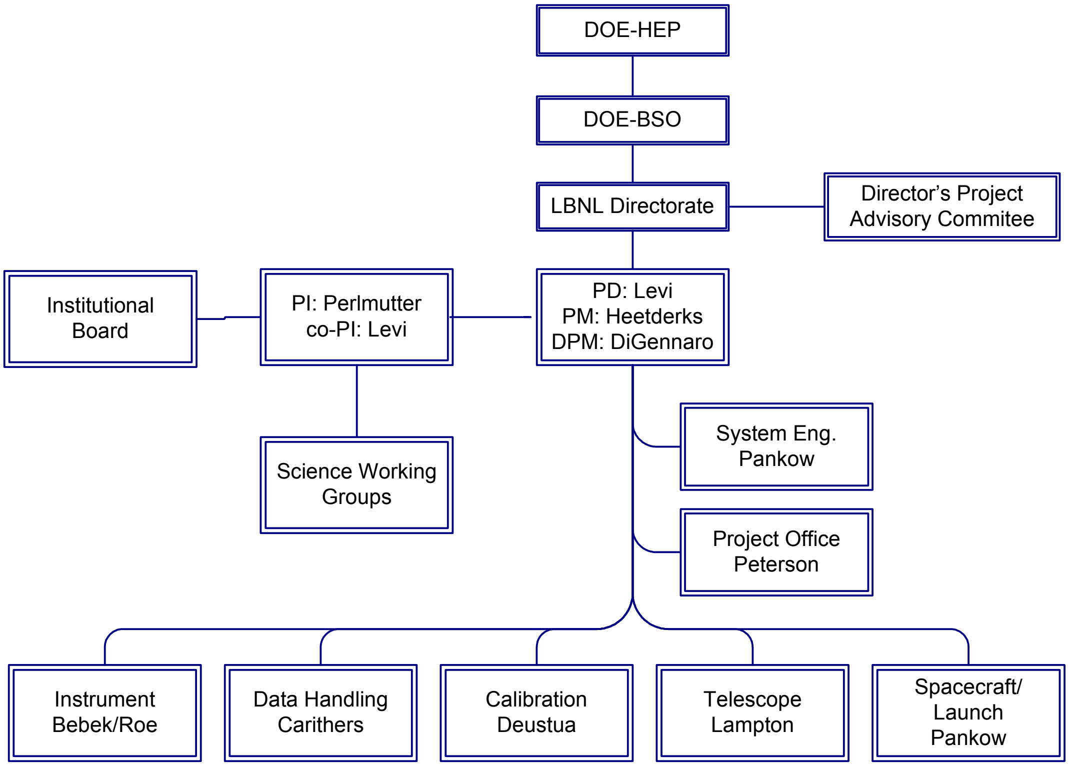

Figure 50. As can be seen in the R&D phase organization chart, the SNAP project is divided into its principal systems and subsystems beneath the Project Directorate. Each major system has a designated System Manager who is responsible for the successful development and completion within budget and schedule constraints.